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A. METHOD FOR EVALUATING SEAKEEPING PERFORMANCE OF DESTROYER FEASIBILITY DESIGNS

LT. DAVID G. KALB 1967

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A METHOD FOR EVALUATING SEAKEEPING PERFORMANCE OF DESTROYER FEASIBILITY DESIGNS

A THESIS

SUBMITTED TO THE FACULTY OF

WEBB INSTITUTE OF NAVAL ARCHITECTURE

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE

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IN

NAVAL ARCHITECTURE

by

LT. DAVID G. KALB, USN

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ABSTRACT

The author discusses a method of determining ship motion responses for a number of destroyer-type hulls which can be evaluated, relative to each other, for their performance in a given sea state. The method is intended to be incorporated in and be compatible with a computer-aided destroyer feasibility study.

A program of the method, along with a discussion, and sample results are presented. Output from the program using the Neumann and the I.T.T.C. wave spectra are compared. Results and supporting data are presented and discussed.

NOMENCLATURE

Ax - Area of maximum section

B - Breadth of ship, LWL

Bx - Maximum breadth of ship, LWL

Cp - Prismatic coefficient of ship

Cx - Maximum section coefficient of ship

H - draft of ship

$H_{1/3}$ - Significant wave height

Hx - Maximum draft of ship

L - Length of ship

LCG - Longitudinal position of center of gravity from forward perpendicular

W - Wind speed

V - Speed of ship

Δ - Displacement of ship

δ - Increment of . . . .

$\Phi_{(\omega e)}$ - Transformed sea spectrum

Φ_{oo} - Amplitude density spectrum of Relative Motion.

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INTRODUCTION

In 1964, when long-range studies of destroyer systems were begun at the Center for Naval Analysis (CNA), it was realized that many systems and their capabilities would have to be considered and analysed. In order to support long-range analyses of costs, effectiveness, trade-offs and sensitiveness of alternative designs, principal characteristics of these ships were required. There were two methods of providing these data: manually, which limits the amount of data on a cost or time limitation, and by computer, if a mathematical model could be developed suitable for computer computation.

Since a large number of ships was to be investigated, the manual method was considered impractical. CNA, with the full cooperation of the Conceptual Design Division (CDD) of the Naval Ship Systems Command (NAVSHIPS), undertook to develop a suitable parametric design model which closely followed the current U.S.Navy design procedures and construction practices. From this work evolved the present "Destroyer Feasibility Study" program currently in use at NAVSHIPS.

The problem of developing a computer feasibility study is one of determining a set of principal dimensions and form coefficients which simultaneously satisfy operational, propulsion, weapons, electronics, weight, moment

and volume requirements. The solution to the problem involves the consideration by computer of a wide range of combinations of these ship characteristics. A unique solution does not exist for a given set of military requirements, rather, a family of ships can be determined for a spectrum of hull lengths and form coefficients.

The computer feasibility study program is a design tool which allows the analyst-designer to consider a varied and wide assortment of ships which are all compatible with the initial conditions of the input data. The designer then must take these ships and narrow the spectrum for a more detailed study. He arrives at his selection and elimination on the basis of costs, powering, payload (weapons) and naval architectural considerations based on current requirements, cost and effectiveness studies, mission fulfillment and his knowledge and experience. He then has a limited group of ships from which the final design may evolve.

The present NAVSHIPS program does not utilize any seakeeping performance data. It would help the analyst-designer if seakeeping performance information were supplied along with the other output data so that in his determination he could evaluate the operational potential of the various ships under consideration when compared to each other in the various sea states.

This presentation demonstrates one approach to the inclusion of such seakeeping evaluation within the feasibility study program.

THE PROBLEM

The output from the aforementioned study lists a number of sets of design parameters from which a series of ships could be designed, each compatible with the requirements used as inputs. (Table I) However, no lines are drawn, there are no body plans, and hence the ships have no delineated form. Seakeeping programs currently in use utilize the strip theory of integration which requires that the ships undergoing analysis have a body plan or at least a water line, half breadths, draft and areas at stations.

The first part of the problem, then, is to develop a program which will give the feasibility ships either a hull form or provide sufficient data from the dimensions and coefficients which then can be utilized in a seakeeping study. The second part is to utilize the hull form developed as an input to a seakeeping analysis computer program. The third part is to analyse the results of the seakeeping output and define useful indices or criteria which will help the analyst-designer in making his final choice.

TABLE I: Sample, Destroyer Feasibility Design printout.

CODE =1-C7 | CP = 0.59 | CX = 0.780 | DATE 10 MARCH 69 | PAGE NO. 5

CHARACTERISTICS										
LBP	450.00	455.00	460.00	465.00	470.00	475.00	480.00	485.00	490.00	495.00
BEAM	55.30	53.45	48.95	48.34	47.93	47.61	47.46	47.30	47.34	47.49
T	19.25	19.22	18.30	18.03	17.83	17.64	17.48	17.34	17.23	17.14
CM	38.21	34.34	34.43	33.92	33.62	33.38	33.27	33.19	33.31	33.54
FBB	21.37	21.50	21.62	21.74	21.85	21.97	22.08	22.19	22.29	22.40
KG	19.77	18.24	18.03	17.80	17.65	17.53	17.47	17.42	17.45	17.52
GM	5.53	5.34	4.89	4.83	4.79	4.76	4.75	4.73	4.73	4.75
GV	2.42	2.15	1.95	1.86	1.78	1.71	1.66	1.60	1.56	1.53
B/H	2.87	2.95	2.68	2.68	2.69	2.70	2.71	2.73	2.75	2.77
VLR	1.41	1.41	1.40	1.39	1.38	1.39	1.37	1.36	1.36	1.35
FS	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
DHP	114518.	103368.	91336.	91296.	89016.	87058.	85567.	84754.	83286.	82558.
PI	114318.	103362.	94336.	91296.	89016.	87058.	85567.	84754.	83286.	82558.
SHPC	16017.	16375.	15672.	15541.	15464.	15411.	15396.	15390.	15424.	15488.
ELKW	2613.	2484.	2380.	2351.	2331.	2319.	2305.	2296.	2293.	2294.
COMPLEMENT										
CLNB	233.	233.	233.	233.	233.	233.	233.	233.	233.	233.
OFFR	19.	19.	19.	19.	19.	19.	19.	19.	19.	19.
CREW	214.	214.	214.	214.	214.	214.	214.	214.	214.	214.
SPACE										
TLV	559727.	485854.	458 [illegible].	443428.	440384.	439228.	441806.	444537.	452133.	462639.
C V	6774.	6446.	5[illegible]743.	5565[illegible].	5567.	5557.	5559.	5556.	5558.	5563[illegible].
AAP	22286.	22052.	2[illegible]712.	20686.	20679.	20681.	20696.	20714.	20767.	20841.
AAES	7097.	7050.	[illegible]968.	6957.	6951.	6946.	6945.	6944.	6947.	6954.
XAAI	0.	127.	0.	0.	0.	279.	670.	1057.	1771.	2698.
NLOX	1.	1.	1.	1.	1.	1.	1.	1.	1.	1.
NDKL	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
WEIGHTS										
DISP	6386.6	6005.3	5492.3	5403.6	5354.0	5318.2	5308.0	5304.3	5327.4	5370.3
W1	1947.5	1708.6	1583.1	1556.1	1544.2	1537.3	1542.8	1549.6	1570.7	1601.4
W2	1252.6	1147.4	1075.5	1049.7	1031.0	1015.3	1003.6	994.0	987.5	983.3
W3	174.7	176.0	176.3	176.7	177.1	177.7	178.3	179.0	179.8	180.7
W4	139.0	131.6	127.3	126.4	126.0	125.8	126.1	126.3	127.1	128.3
W5	570.2	488.4	442.6	430.1	422.1	417.9	416.2	415.1	417.5	422.2
W6	266.5	245.7	235.1	232.8	231.9	231.5	232.3	233.1	235.4	238.6
W7	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
MARG	441.7	395.9	360.9	363.2	359.3	356.5	355.9	355.7	357.8	361.4
WL	4859.1	4354.7	4 [illegible]69.7	3995.0	3952.7	3922.0	3915.4	3912.8	3935.9	3975.9
FGM	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
COMP	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1
PROV	34.1	34.1	34.1	34.1	34.1	34.1	34.1	34.1	34.1	34.1
GENS	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1
[illegible]	51.9	51.9	51.9	51.9	51.9	51.9	51.9	51.9	51.9	51.9
REM	107.4	98.2	91.6	89.4	87.7	86.4	85.1	84.2	83.5	82.9
LOAD	21.4	19.2	18.2	17.9	17.6	17.4	17.2	17.1	17.0	16.9
FULL	1146.4	1109.7	1 [illegible]67.5	1058.6	1053.4	1049.6	1048.2	1047.4	1049.0	1052.4
SWBD	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
AMMO	71.8	71.8	71.8	71.8	71.8	71.8	71.8	71.8	71.8	71.8
A/C	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
MPS	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
WFL	6376.2	5825.8	5490.5	5404.8	5355.4	5319.2	5309.9	5305.5	5329.4	5372.2
NDIT	14	14	11	8	8	9	8	8	6	6
COSTS										
CCFS	42.873	39.933	38.201	37.755	37.5[illegible]1	37.316	37.277	37.261	37.400	37.641

COSTS										
LBP	450.00	455.00	460.00	465.00	470.00	475.00	480.00	485.00	490.00	495.00
CCFS	42.673	39.943	38.201	37.755	37.581	37.516	37.277	37.261	37.400	37.641
BASE	32.398	30.418	28.716	28.270	28.016	27.851	27.792	27.776	27.915	28.156
PLAN	18.859	16.355	16.069	15.995	15.953	15.922	15.915	15.913	15.936	15.976
ELEC	4.900	4.900	4.900	4.900	4.900	4.900	4.900	4.900	4.900	4.900
WEAP	2.400	2.400	2.400	2.400	2.400	2.400	2.400	2.400	2.400	2.400
LEAD	59.732	56.257	54.270	53.750	53.494	53.289	53.192	53.174	53.336	53.617
DECK HEIGHTS AT CENTERLINE										
L2P	450.00	455.00	460.00	465.00	470.00	475.00	480.00	485.00	490.00	495.00
DFP	43.92	45.12	45.50	45.66	45.70	45.68	45.85	45.87	45.75	45.56
D5	39.20	36.81	36.92	36.60	36.36	36.24	36.17	36.12	36.17	36.29
D10	36.96	32.00	32.09	31.37	30.89	30.67	30.56	30.47	30.62	30.94
D15	36.59	30.71	30.72	29.97	29.72	29.63	29.61	29.90	29.80	29.48
DAP	38.10	32.91	32.10	32.39	32.25	31.98	31.52	31.44	31.60	31.93
MACHINERY SPACE										
DME	33.29	32.00	31.62	30.69	30.44	30.32	30.06	29.92	29.81	29.73
MBL	207.27	197.57	190.16	187.56	185.60	183.93	182.66	181.54	180.71	180.09
CUBIC NUMBER OF HULL										
CN	9.-1	8.35	7.75	7.63	7.57	7.54	7.55	7.62	7.73	7.88
SPEED - POWER										
LBP	450.00	455.00	460.00	465.00	470.00	475.00	480.00	485.00	490.00	495.00
VLP										
.5	10.61	10.67	10.72	10.78	10.84	10.90	10.95	11.01	11.07	11.12
	1907.58	1867.53	1852.03	1879.47	1900.95	1924.16	1933.49	1977.71	2008.50	2042.02
.6	12.73	12.80	12.87	12.94	13.01	13.08	13.15	13.21	13.28	13.35
	3132.37	3122.55	3086.59	3136.71	3193.89	3257.25	3326.02	3390.25	3472.86	3554.44
.7	14.89	14.93	15.01	15.09	15.18	15.26	15.34	15.42	15.50	15.57
	5595.78	5359.29	5290.79	5374.84	5471.72	5572.35	5683.21	5796.67	5921.21	6054.35
.8	16.97	17.06	17.16	17.25	17.34	17.44	17.53	17.62	17.71	17.80
	8647.25	8016.09	8429.63	8540.10	8673.04	8816.34	8977.89	9143.50	9330.46	9533.41
.9	19.09	19.20	19.30	19.41	19.51	19.62	19.72	19.82	19.92	20.02
	13095.63	12691.88	12577.42	12721.60	12903.55	13102.01	13331.65	13567.75	13838.52	14135.56
1.0	21.21	21.33	21.45	21.56	21.68	21.79	21.91	22.02	22.14	22.25
	18886.57	18614.09	18026.41	18163.02	18362.46	18587.90	18859.62	19144.21	19483.98	19862.57
1.1	23.33	23.46	23.59	23.72	23.85	23.97	24.10	24.22	24.35	24.47
	24891.12	25673.59	24293.04	24463.38	24719.71	25012.96	25372.85	25749.51	26198.55	26731.55
1.2	25.46	25.60	25.74	25.88	26.02	26.15	26.29	26.43	26.56	26.70
	30428.36	35131.19	33694.49	33765.56	33985.22	34262.96	34641.37	35045.65	35558.66	36151.97
1.3	27.58	27.73	27.88	28.03	28.18	28.33	28.48	28.63	28.78	28.92
	52814.74	50022.71	47730.35	47524.84	47604.24	47777.99	48119.09	48507.58	49069.86	49761.27
1.4	29.70	29.86	30.03	30.19	30.35	30.51	30.67	30.83	30.99	31.15
	75911.88	71307.48	66722.86	66189.04	66060.95	66098.43	66410.48	66800.93	67473.36	68366.18
1.5	31.82	32.00	32.17	32.35	32.52	32.69	32.86	33.03	33.20	33.37
	103176.23	95703.21	88458.84	87521.21	87177.80	87056.12	87321.61	87700.83	88500.20	89589.10
1.6	33.94	34.13	34.32	34.50	34.69	34.87	35.05	35.24	35.42	35.60
	132022.81	121371.69	112310.80	111061.13	110597.63	110422.12	110764.08	111275.58	112298.58	113694.58
1.7	36.06	36.26	36.46	36.66	36.86	37.05	37.25	37.44	37.63	37.82
	162590.49	149737.35	1386[illegible].92	137139.46	136652.46	136569.21	137235.41	138072.93	139553.82	141310.29
1.8	38.18	38.40	38.61	38.81	39.02	39.23	39.44	39.64	39.84	0.
	196451.76	181897.68	168987.29	167731.15	167666.38	168315.33	169720.76	171329.42	173722.23	0.
1.9	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
2.0	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
VTPI	32.66	32.69	32.72	32.71	32.70	32.69	32.69	32.69	32.69	32.67
VSPI	30.04	30.04	30.03	30.02	30.01	30.00	30.00	30.00	30.01	30.02

450.00 4000. 594 1785. 4 1000. 3 0.59 169. 2740. 344. 1311. 118. 344370.

out.

480.00	485.00	490.00	495.00
47.43	47.30	47.34	47.49
17.46	17.34	17.23	17.14
33.27	33.19	33.31	33.54
22.08	22.19	22.29	22.40
17.47	17.42	17.45	17.52
4.75	4.73	4.73	4.75
1.66	1.60	1.56	1.53
2.71	2.73	2.75	2.77
1.37	1.36	1.36	1.35
.69	0.69	0.69	0.69
85567.	84754.	83286.	82558.
85567.	84754.	83286.	82558.
15396.	15390.	15424.	15488.
2295.	2296.	2293.	2294.
233.	233.	233.	233.
19.	19.	19.	19.
214.	214.	214.	214.
13331.65	13567.75	13838.52	14135.56
21.91	22.02	22.14	22.25
18859.62	19144.21	19483.98	19862.57
24.10	24.22	24.35	24.47
25372.85	25749.51	26198.55	26701.55
26.29	26.43	26.56	26.70
34641.37	35045.65	35558.66	36151.97
28.48	28.63	28.78	28.92
48119.09	48507.58	49069.86	49761.27
30.67	30.83	30.99	31.15
66410.48	66800.93	67473.36	68366.18
32.86	33.03	33.20	33.37
87321.61	87709.83	88500.20	89589.10
35.05	35.24	35.42	35.60
110764.08	111275.58	112298.58	113694.58
37.25	37.44	37.63	37.82
137235.41	138073.93	139553.82	141510.29
39.44	39.64	39.84	0.
169720.76	171329.42	173722.23	0.
0.	0.	0.	0.
0.	0.	0.	0.
0.	0.	0.	0.
0.	0.	0.	0.
32.69	32.69	32.69	32.67
30.00	30.00	30.01	30.02
1311.	118.	344370.	

THE SOLUTION - PART I

A solution to the first part of the problem involves the development of a method which will compute the hull form inputs (beam, draft and section area coefficient for each of 20 stations along the hull) required for a seakeeping program.

A current project at NAVSHIPS is the updating and revision of the feasibility study program. From a comprehensive study of the destroyer-type ship conducted over a period of years, a parent hull was developed by Mr. James Mills[1]. From this parent, four other hulls were derived by Mills, which took into account the upper and lower ranges of destroyer-type parameters. The five ships were then placed in the Y-G Hull program [2] and relationships among the hulls were analysed for the purpose of refining deck area and volume calculations in the feasibility study.

This previous utilization by Mills of a parent and four derivatives for the non-seakeeping part of the feasibility study suggested a possible modus operandi to the author for

[1] See Confidential Annex.

[2] The Y-G Hull computer-program was developed by G. Hirschberg and Lt. R. Warters, for computing any or all of six options: 1) Hydrostatics and Bonjean curves, 2) Compartment volumetric properties, 3) Longitudinal Strength, 4) Floodable Length, 5) Limiting Drafts, 6) Intact cross curves of stability. The primary input data are the offsets of the hull and LBP.

arriving at a method of computing the needed hull form or input parameters when lines are not available. An empirical relationship from this series for area, beam and draft seemed possible and this was the approach taken.

The two parameters which had been varied in the five ships were prismatic coefficient and midship section coefficient. In order to avoid a three-dimensional problem, one of the variables had to be held constant to reduce the problem, to two dimensions.

After a series of discussions with personnel in the Hydromechanics Laboratory of David Taylor Model Basin (DTMB) concerning the effects of Cp and Cx on ship motions, it was decided that the effects of varying Cx were very small when compared to varying Cp. Cx was then chosen as the one to be kept constant for the purpose of development of the interpolation program. However, it was anticipated that a variable Cx could be reincorporated in the final program.

With due consideration for the above decision the following method was developed.

Values of local beam and draft for the twenty stations of all five ships were lifted from the body plans and non-dimensionalized by dividing by Bx and Hx. Areas at each station were computed by the Y-G Hull program and also non-dimensionalized by dividing by Ax. These non-dimensional values were then plotted against Cp, the variable, for each of the 20 stations (Figs. C-1, C-2, C-3).[3]

[3]Confidential Annex

Simultaneously these values were put into a least squares polynomial curve-fitting computer program and equations using Cp as the variable were computed for each of the twenty stations. Twenty equations for non-dimensional area, twenty equations for non-dimensional beam and seven equations for non-dimensional draft were computed. (Draft is constant from station zero to station 14 where the transom line intersects the base line.)

The resulting equations were checked for accuracy and then written as a controlling program for supplying hull form inputs to a seakeeping program (to be discussed in the next section) currently available at DTMB.

The controlling program solves the series of equations using Cp as the variable. The resulting non-dimensional values of area, beam and draft are then dimensionalized by multiplying by the actual input values of maximum sectional area, maximum beam and maximum draft. Section area coefficients are then computed for the twenty stations. The computed values of beam, draft and section area coefficient are then stored in the computer-memory for use by the seakeeping program.

At this point the question of the validity of reintroducing Cx as a variable in the equation: $Ax = Cx \cdot Bx \cdot Hx$, arose. (It will be recalled that Cx was temporarily kept constant for the purpose of developing the interpolation curves and resulting equations). To justify the validity

of this reintroduction, the parameters of two of the five original ships, which varied from the assumed constant value of Cx, were run through the control program. A comparison of this output with respect to sectional areas was made with the more exact areas computed by the more detailed Y-G Hull calculations. The differences were very small (See confidential annex) and are insignificant when considering ship motions. This comparison led to the conclusion that Cx can be reintroduced into the program as a variable when computing maximum section area.

The first part of the original problem was then considered solved. The input variables of Cp, Cx, Bx and Hx could now be developed into a mathematical hull which was compatible with the ships arrived at in the feasibility study, using the output of the feasibility program as input. Section area curves as computed by the control program are shown in Figures I and II.

THE SOLUTION - PART II

The seakeeping program selected for use with the control program was developed at Massachusetts Institute of Technology under a NAVSHIPS contract as part of the Fundamental Hydromechanics Research Program administered by DTMB.[18] It was originally written by K. Haslum, making use of subroutines from Stevens Institute of Technology which utilize the Korvin-Kroukovsky theory for computing added mass and hull damping coefficients. It was later expanded by L. Vassilopoulos to include statistical responses in irregular seas applying a Neumann energy spectrum. This program will be referred to hereafter as the MIT program. This program was revised by N. Salvesen [11] at DTMB, to include a plot routine (not utilized in this study), changes in input-output format, changing to FORTRAN IV computer language and adding speed contributions to the computed coefficients according to the theory of Tuck.[3] (The program still remains basically the MIT program).

The MIT Program computes pitch and heave amplitudes and their phase angles in regular head seas, calculates bending moments and computes several statistical responses in irregular head seas. The particular statistical response used in the present study was the root mean square value

[3]Unpublished work by Tuck at DTMB

of relative vertical motion at station 2. The relative vertical motion refers to the distance between the water surface and the DWL as the ship responds to the seaway.

The MIT Program was used for determining the statistical responses for thirteen (13) hull forms; the original five ships from which the equations previously mentioned were derived plus an additional eight (8) test ships (TABLE II) taken from the output of the Destroyer Feasibility program, mentioned in the Introduction.

The author then changed the subroutine that calculates the sea spectrum by the Neumann equation to a new subroutine that utilizes the International Towing Tank Conference, 1966 [22] , equation, changing from wind speed input to wave height input. (FigureIII) The 13 ships were then run through this program.

The input information to both programs mentioned above is the same with the exception that significant wave height values are substituted in the latter for significant wind speed values in the former. The ITTC spectra were used by the author since they are more realistic. A comparison of the two spectra and the resulting response spectra is shown in Figure IV, for one case.

Information not calculated by the feasibility program, radius of gyration and longitudinal center of gravity, was set at .25L and .50L respectively. These values are commonly

TABLE II: FEASIBILITY TEST SHIP CHARACTERISTICS

DESIGN NO.		1	2	3	4	5	6	7	8
Max. Beam,	Bx	48.94	47.85	47.64	48.71	47.86	48.51	47.65	48.04
Max.Draft,	Hx	18.42	17.83	17.44	17.71	16.85	17.08	16.57	16.31
	Cp	0.58	0.58	0.58	0.59	0.59	0.60	0.60	0.60
	Cx	0.78	0.78	0.78	0.79	0.79	0.80	0.80	0.80
Length	L	465.0	480.0	495.0	465.0	495.0	465.0	480.0	495.0
Displacement (TONS)		5495.1	5368.7	5391.1	5418.0	5392.1	5358.3	5272.8	5395.1
Assumed Radius of Gyration .25L		116.25	120.00	123.75	116.25	123.75	116.25	120.00	123.75
Assumed LCG .5L		232.50	240.00	247.50	232.50	247.50	232.50	240.00	247.50

used in initial design studies. Other input values are as follows:

Number of stations	20
Ship speed	10 to 30 knots
Significant Wave Height ($\bar{H}_{1/3}$)	14.5 to 48.0 feet
Frequency of encounter*	.10 to 3.10 rad./sec

These were held constant for all ships. The variables were the ships themselves with beam, draft and station sectional area coefficients computed by the control program described in Solution Part I.

*Calculated range to encompass the maximum area under the response spectrum which would give accurate values of response.

THE SOLUTION - PART III

The format of the printout of the seakeeping program, described in Appendix A, allows the analyst to select from a number of statistical values of response. The square root of the area under the squared amplitude density spectrum of relative motion at the "slamming station" (.1L aft of FP or station 2) is calculated by the program. These r.m.s. values were tabulated for each ship and used in line 3 of the probability tabulation. (TABLE V)

The seakeeping criterion chosen for investigation is sonar dome immersion for a dome mounted at .1L from FP at the ship's base line.

If one accepts the hypothesis that the sonar will always function properly if its dome remains at least one foot below the water surface, a criterion of performance can be established which expresses the limit of operability of bow mounted sonar in terms of the frequency that the relative bow motion exceeds the draft of the vessel minus one foot. If this criterion is applied directly to the calculated r.m.s. motions, a limiting r.m.s. value can be selected which has a value of (H - 1) feet for each ship considered.

A wave height frequency of distribution of the spectra can then be selected. The distribution used by the author is based on that given in [2] for the North Atlantic and is given in TABLE IV. This is not a particularly severe

TABLE IV

ASSUMED DISTRIBUTION OF WAVE HEIGHTS ($H_{1/3}$) FOR NORTH ATLANTIC

Significant Wave Height (ft)	Assumed Percentage of occurrance (%)
14.5	73.70
14.5	15.60
21.2	6.90
27.9	3.10
34.9	.45
41.3	.20
48.0	.05
	100.00%

Feasibility Design Number 8 σ = .16(Σ line 4)

1	Wave Category-ft.	14.5	14.5	21.2	27.9	34.6	41.3	48.0	
2	Wave Frequency	.737	.156	.069	.031	.0045	.0020	.005	
3	rms value rel.motion	2.18	4.81	7.00	8.81	11.30	14.47	17.66	
4	Product lines 2x3	1.61	.75	.48	.27	.051	.029	.009	Σ=3.199
5	x = 5.9 - line 3	7.25	2.13	-2.14	-5.67	-10.56	-16.74	-22.97	σ=.512
6	Probability of not exceeding rms=5.9	1.00	.9834	.0162	0.0	0.0	0.0	0.0	
7	Lines 2 x 6	.737	.153	.001	0.0	0.0	0.0	0.0	Σ=.890

Ship Speed 10 Knots

1	14.5	14.5	21.2	27.9	34.6	41.3	48.0	
2	.737	.156	.069	.031	.0045	.0020	.005	
3	2.28	5.18	7.79	9.92	12.07	14.82	17.90	
4	1.68	.81	.54	.31	.054	.030	.009	Σ=3.433
5	7.68	1.31	-3.44	-7.31	-11.24	-14.79	-21.85	σ=.549
6	1.00	.9049	.0003	0.0	0.0	0.0	0.0	
7	.737	.141	0.0	0.0	0.0	0.0	0.0	Σ=.878

Ship Speed 15 Knots

1	14.5	14.5	21.2	27.9	34.6	41.3	48.0	
2	.737	.156	.069	.031	.0045	.0020	.005	
3	2.54	5.54	8.46	11.0	13.18	15.59	18.41	
4	1.87	.86	.58	.34	.059	.031	.009	Σ=3.749
5	5.61	.60	-4.27	-8.50	-12.14	-16.15	-20.85	σ=.600
6	1.00	.7257	0.0	0.0	0.0	0.0	0.0	
7	.737	.113	0.0	0.0	0.0	0.0	0.0	Σ=.850

Ship Speed 20 Knots

1	14.5	14.5	21.2	27.9	34.6	41.3	48.0	
2	.737	.156	.069	.031	.0045	.0020	.005	
3	2.80	5.96	9.20	12.10	14.48	16.75	19.28	
4	2.06	.93	.63	.36	.065	.034	.010	=4.089
5	4.74	-.09	-5.04	-9.48	-13.12	-16.59	-20.46	σ=.654
6	1.00	.4641	0.0	0.0	0.0	0.0	0.0	
7	.737	.072	0.0	0.0	0.0	0.0	0.0	=.809

Ship Speed 25 Knots

1	14.5	14.5	21.2	27.9	34.6	41.3	48.0	
2	.737	.156	.069	.031	.0045	.0020	.005	
3	3.00	6.40	10.05	13.20	15.84	18.15	20.50	
4	2.21	1.00	.69	.41	.071	.036	.010	Σ =4.427
5	4.09	-.71	-5.85	-10.31	-14.04	-17.30	-20.62	σ=.708
6	1.00	.2389	0.0	0.0	0.0	0.0	0.0	
7	.737	.037	0.0	0.0	0.0	0.0	0.0	Σ=.774

Ship Speed 30 Knots

NOTE: FOR DETAILED EXPLANATION. SEE APPENDIX C.

distribution and could easily be altered as desired to represent other ocean areas or heavy weather conditions.

To perform a probability analysis of the ship's motions a measure of the variability of r.m.s. response within each sea condition is required. A value of the ratio of standard deviation (σ) of r.m.s. relative motion to mean r.m.s. value equal to 0.16 was selected from [2]. To demonstrate the method and reduce calculations this value of σ/m was used for all ships at all speeds. More accurate σ/m values can be calculated by computing ship responses to a randomly selected group of sea spectra in several ranges of sea severity as was done in [2].

It was assumed that the destroyers being analysed could perform their mission if their sonar was operable for 96% of the motion cycles over a particular short term situation, for example, one watch during a patrol. This means that 4% of the relative bow motion peaks experienced would be greater than (H - 1) feet, causing the sonar dome to rise to less than one foot below the surface, making it inoperable.

If relative bow motion is Rayleigh distributed and subject to a limit of (H - 1) feet with a 96% probability of operable sonar time, the corresponding limiting r.m.s. value from probability theory is .39 times (H - 1). In the case shown in TABLE V, where draft is 16.31 feet, 15.31 x 0.39 = 5.9.

Taking all of the above into account, a tabular format for calculating the probable performance of the ships was set up as given in [23] and used in [2] . Five ships with the widest variance of parameters were used, in lieu of calculating all eight, in order to show clearly the differences in performance. The result of each tabular calculation is the overall percent of time the ship could be expected to perform its mission in different head seas in the assumed long term wave distribution. A sample tabulation is shown in TABLE V for one particular ship at several speeds.

The results of all the tabulations are then plotted as a function of ship speed (Figures V & VI) and show the overall performance of each ship over the speed range. The figure shows that designs 5 and 8 have definite superiority and could patrol in the North Atlantic at speeds above 25 knots better than 77% of the time while achieving satisfactory sonar performance.

The method proposed by the author results in a prediction of the percent of time a ship could be expected to perform a given mission satisfying a particular seakeeping criterion. A group of ships with varying characteristics, such as the feasibility program provides, can thus be compared relative to each other based upon their predicted performance.

The criterion used in this study is an example, and other limiting values and probabilities may be more appropriate. The r.m.s. value used in line 5 of TABLE V can be read from Figure VII for any limiting value and any probability.

ANALYSIS OF RESULTS

The final results of this study are the performance curves which show the predicted performance of the ships. The trends of performance for the variation of hull characteristics are consistent with trends studied in [19], [23] and [2] . The longest ships, 5 and 8, are shown to perform the best of the eight feasibility ships. Since dimensions and coefficients, other than length, are very close in these designs, this result is believed to represent the effect of length. Ship number 5 is slightly better than 8, on the performance curves. (It will be noted that on FIGURES VIII thru XIII ship number 5 shows a greater relative motion than ship number 8. This would lead one to believe that ship number 8 is the better ship. However, for the criterion under investigation ship number 5 performs better. This is due to the deeper draft of number 5. The deeper draft then, offsets the slight disadvantage of motion for this criterion.). Design number 1 is the worst performer due to a number of possible factors; among them, shorter length, smaller Cp and reduced beam to draft ratio.

The author feels that the variation in length among the 8 feasibility designs overrides the effects of small variations in other parameters. Here is where the analyst can apply his knowledge. The longer ships may perform better but they usually cost more. Is the increased effectiveness of designs 5 and 8 worth the cost of increasing length? Using Figure V, a 4% increase in effectiveness of these designs over design 1, at 25 knots may not justify

the increase in length of 25 feet. That decision is left to the analyst.

For the five JLM ships, length, beam and draft were constant thereby allowing a check on proper trends with the variation of Cp and Cx alone. Trends have been studied by L. Vassilopoulos [19] for a series of Mariner-type hulls. This study showed an increase in Cp, while reducing Cx reduces ship response, and an increase in Cx while reducing Cp, increases ship response; the greater effect being caused by varying Cp. The JLM designs bear this out. Ship JLM-1 is the worst performer, relative to the others, since it has the lowest Cp. Ship number three is best to 26 knots due to its high Cp. Above 25 knots the curves of JLM's 3 and 4 cross giving 4 the advantage at 30 knots. The same thing happens between JLM's 1 and 5. The crossing is probably attributable to the larger displacements of ships 3 and 5. From this one could say the ship with the smaller displacement has better seakeepability at high speeds, but it will not necessarily meet the same military requirements as the larger ship. A systematic study of seakeeping trends by varying parameters is recommended in the next section.

The analysis of the 8 feasibility ships were kept separate from the 5 JLM ships. The curves of r.m.s. relative motion vs. ship speed (Figures VIII through XIII) showed

a definite difference in r.m.s. response between the two groups, especially at the lower significant wave heights. JLM-2 and feasibility design 7 curves were expected to appear fairly close together since their characteristics have only small differences. They were not close together and had different shapes. This led the author to keep the two groups separate pending further study. Inputs to the seakeeping subroutine appeared correct for all 13 ships but the comparative shape of the response curves showed an unaccountable difference. This type of study is beyond the scope of this thesis but definitely should be carried out before the program is used.

The performance curves (Figures V and VI) are an excellent way to compare a varied number of ship designs. The individual differences in performance due to variation of parameters and dimensions are weighted and compared statistically so that the final result is a direct comparison of performance only, based on the chosen criterion.

The overall result of this thesis then is the establishment of a logical method of evaluating the seakeeping performance of a variety of ships during the feasibility design stage from predicted performance curves based upon selected criteria, and applicable to computer calculation.

CONCLUSION

The main objective of this thesis has been the establishment of a method whereby an analyst-designer would be able to assess the seakeeping performance of many ship designs while still in the feasibility stage using currently available computer programs and techniques. This has been done. The resulting performance curves can be used directly by the designer to evaluate the probable performance of a large number of ships. Comparisons can be made and decisions arrived at which would allow trade-offs in performance, costs, and meeting military requirements.

No attempt was made by the author to establish trends in seakeeping performance by varying ship characteristics. It has been shown [2], [18], [23], that increasing the length to draft ratio and beam to draft ratio tend to improve response. An increase in waterplane inertia by increasing beam, holding Cx and draft constant, leads to V-form section shapes. V-forms perform very favorably in a seaway as was demonstrated in [2] and shown here by the high performance of JLM-4 in Figure VI.*

Ships of longer length hold a definite advantage in reduction of ship motions. However, draft is also beneficial when evaluating certain criteria, such as sonar dome immersion. Deeper draft vessels tend to have less overall bow relative motion, keeping the sonar dome immersed. This fact also would help to reduce slamming and water over the deck. Altering a particular hull parameter in order to improve a design's seakeepability necessitates a careful review of the effects on other parameters which may be changed by the alteration, causing adverse effects, possibly offsetting the desired improvement. The technique presented permits this to be done.

*See body plan in Confidential Annex.

DISCUSSION AND RECOMMENDATIONS

The predicted performance curves arrived at as a result of this thesis apply only to the assumed criterion of sonar dome immersion. A more detailed seakeeping analysis of a group of ships would include performance curves based on other criteria. The present program computes statistical values for acceleration and velocity of bow relative vertical motion, stern acceleration and pitch angle. Any criterion, once established, that would make use of the above statistical values could be investigated using the proposed method. For example, an analysis involving slamming would make use of the statistical values computed for bow relative vertical acceleration. The proposed method could be used after establishing a criterion limiting the relative acceleration to a value which would not produce slams. For further discussions of particular proposed seakeeping criteria see [2] and [18].

The predicted performance calculations are not programmed. The complete computer study would involve programming these calculations as a subroutine at which time the selected seakeeping criteria may be included.

The present program is written for only ahead, irregular, long crested seas. For complete analysis the calculation of ship motions at all headings and the ability to analyse ship responses in short-crested seas should be made

as available subroutines to be called as the user desires.

One must not forget, however, that the application of a seakeeping study at the feasibility stage requires rapid analysis of a great number of computer designs. Any lengthening of the program should be considered carefully. The program as used herein is already large and considered by the author to need careful revision before it can be included as a subroutine to a computer feasibility study. (To compute the analysis of one ship used in this study required a minimum of one hour; 5 minutes on the IBM7090 computer, 5 minutes to print the output, and 50 minutes to tabulate and calculate the predicted performance percentages.) Calculations using fewer ship speeds and larger increments of frequency of encounter will reduce computer time, but the major reduction would have to be program revision based upon future work in simplifying the ship motion computations.

Due to the number of ship characteristics required as input to the program, the author believes a study of the effects of variation of hull parameters on ship response might well be carried out. A variation of any one or a combination of the input parameters, Cx, Cp, B, H, L, Δ, LCG and radius of gyration, carried out in a systematic manner would establish definite trends in overall ship response. The naval architect would then be able to focus his attention

on the combinations of ship characteristics which would result in a ship with good seakeeping qualities.

The control program written by the author can be used with any seakeeping program where values of beam, draft and section area coefficients are used to calculate the ship responses. It can be detached from the seakeeping subroutine used by the author and by changing a few statements attached to any new or improved seakeeping program. It can also be used alone to provide a designer with points on a sectional area curve or points on a load water line curve. These curves will, however, form a family with the JLM designs.

The complete program, called KSEA, is not in its ideal form. During this study the subroutines would not directly accept the data computed by the control program. Cards had to be punched by the control program then fed to the subroutines even though the data was identical to that stored in the memory of the computer. This should be corrected so the program will be continuous. The subroutines should be revised to compute motion and its derivatives at the forward perpendicular as well as the slamming station. The probability analysis of Solution - Part III, should be programmed and made a subroutine of KSEA, possibly using a plotting routine to plot performance curves. These additions and revisions would make KSEA a functional design

computer program accepting as input, Cp, Cx, Bx, Hx, Δ, and L from the feasibility study and giving the designer a performance curve, based upon the selected criterion, which he can use directly in his evaluation of the designs.

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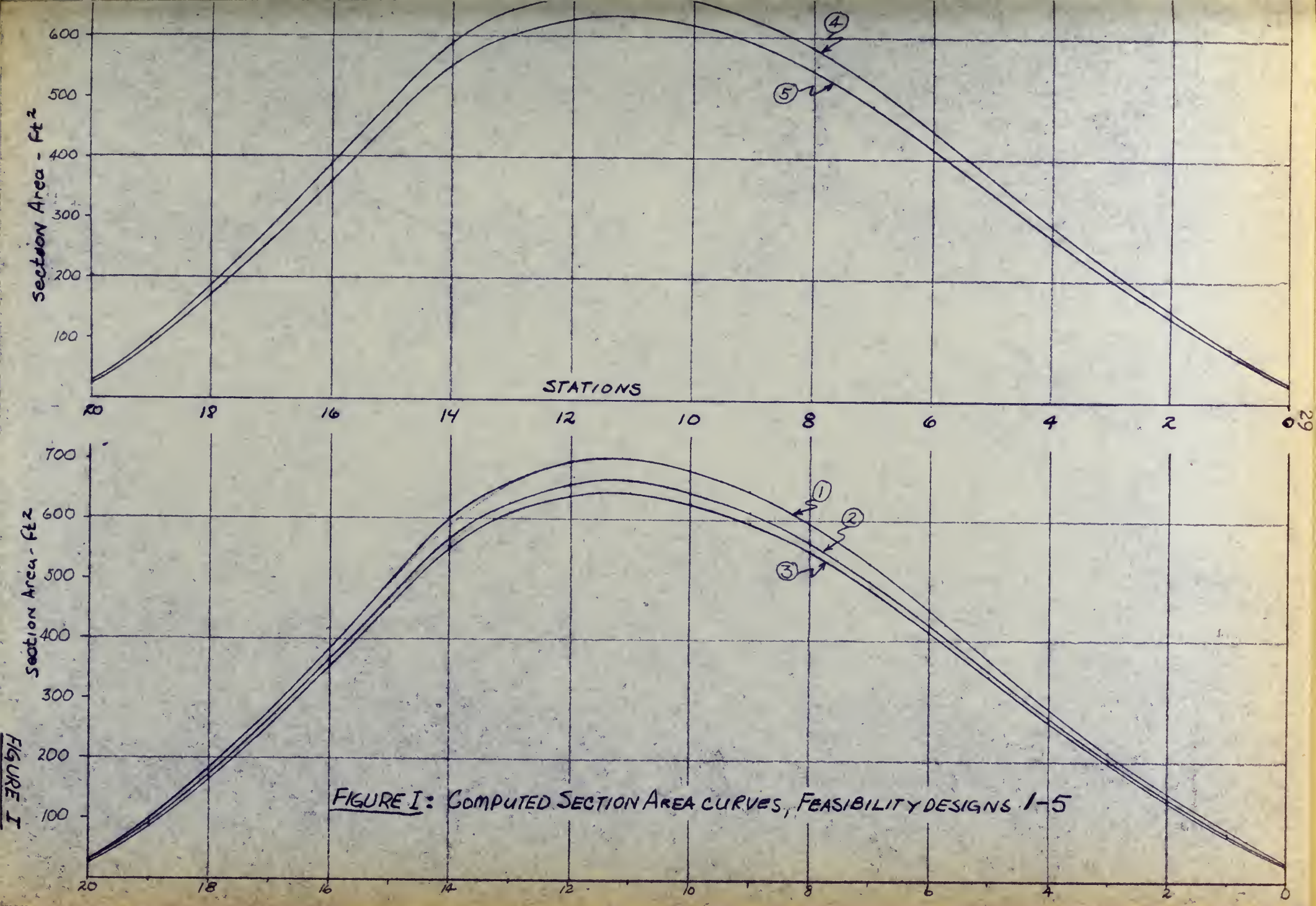


FIGURE I: COMPUTED SECTION AREA CURVES, FEASIBILITY DESIGNS 1-5

FIGURE I

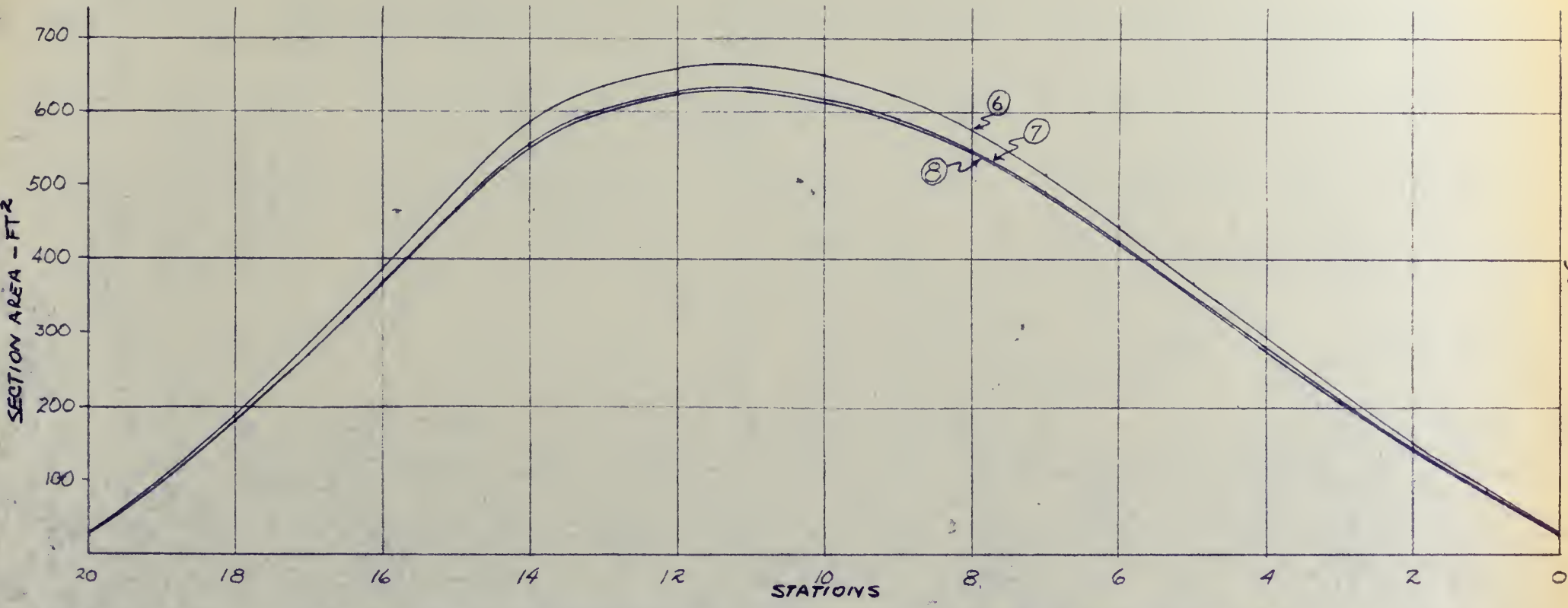
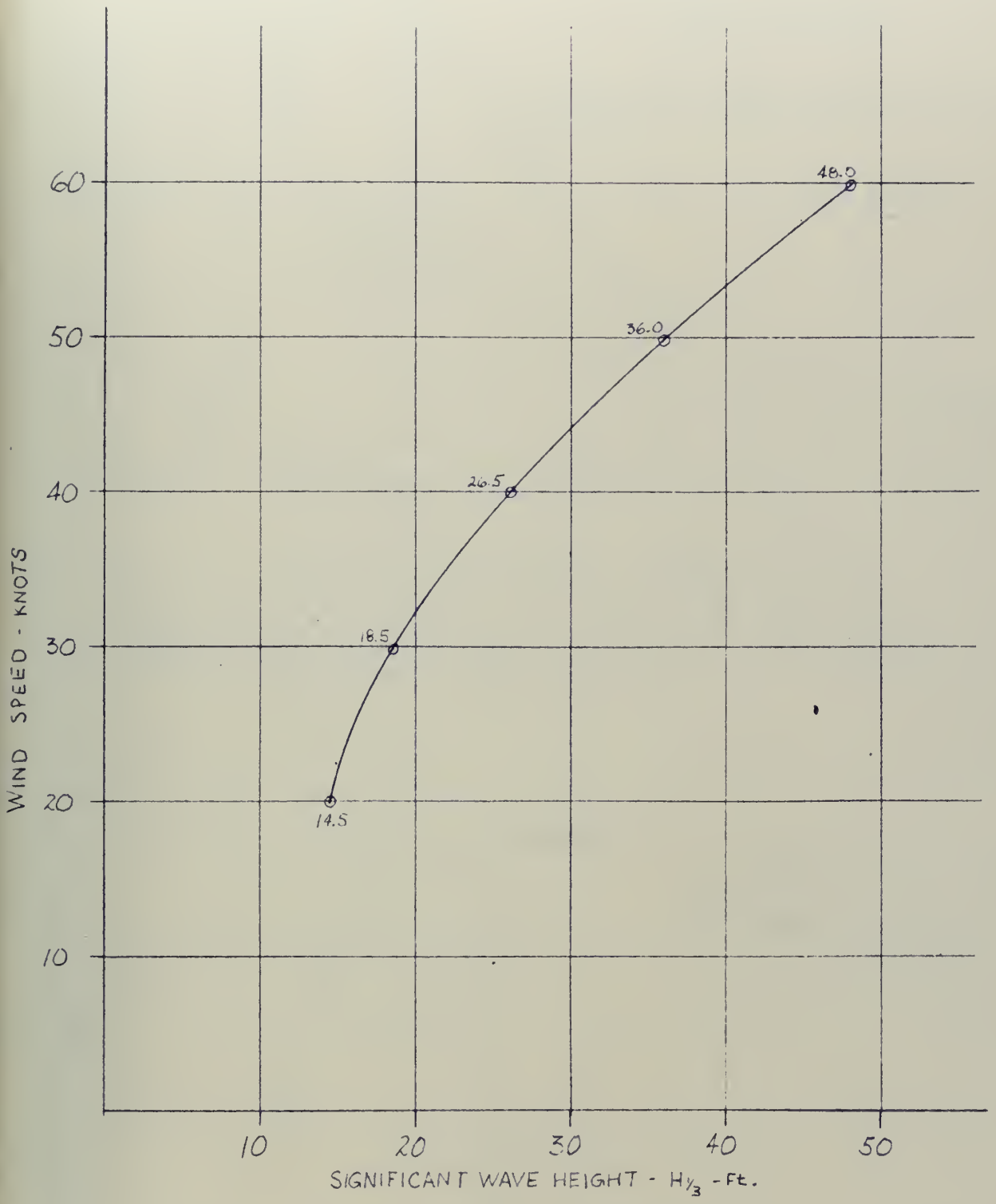


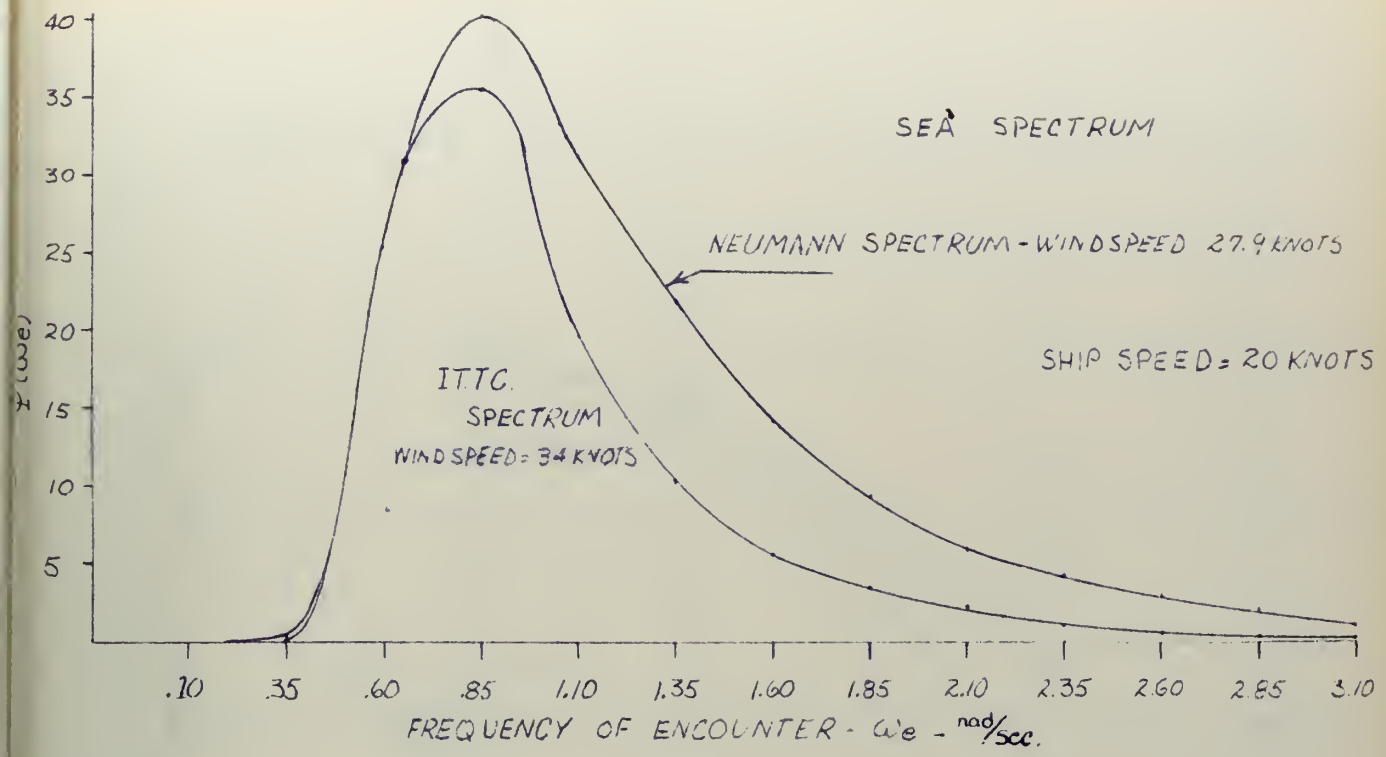
FIGURE II : COMPUTED SECTION AREA CURVES, FEASIBILITY DESIGNS 6-8.



I.T.T.C 1966 Conference Spectrum

WIND SPEED – SIGNIFICANT WAVE HEIGHT CURVE

FIGURE III



TYPICAL SPECTRUM CURVES SHOWING GREATER SEVERITY OF NEUMANN SPECTRUM AS COMPARED TO THE I.T.T.C. SPECTRUM. BELOW SHOWS RESULTING AMPLITUDE DENSITY SPECTRUM (RESPONSE SPECTRUM) WHEN THE SAME SHIP IS INVESTIGATED IN BOTH SPECTRA.

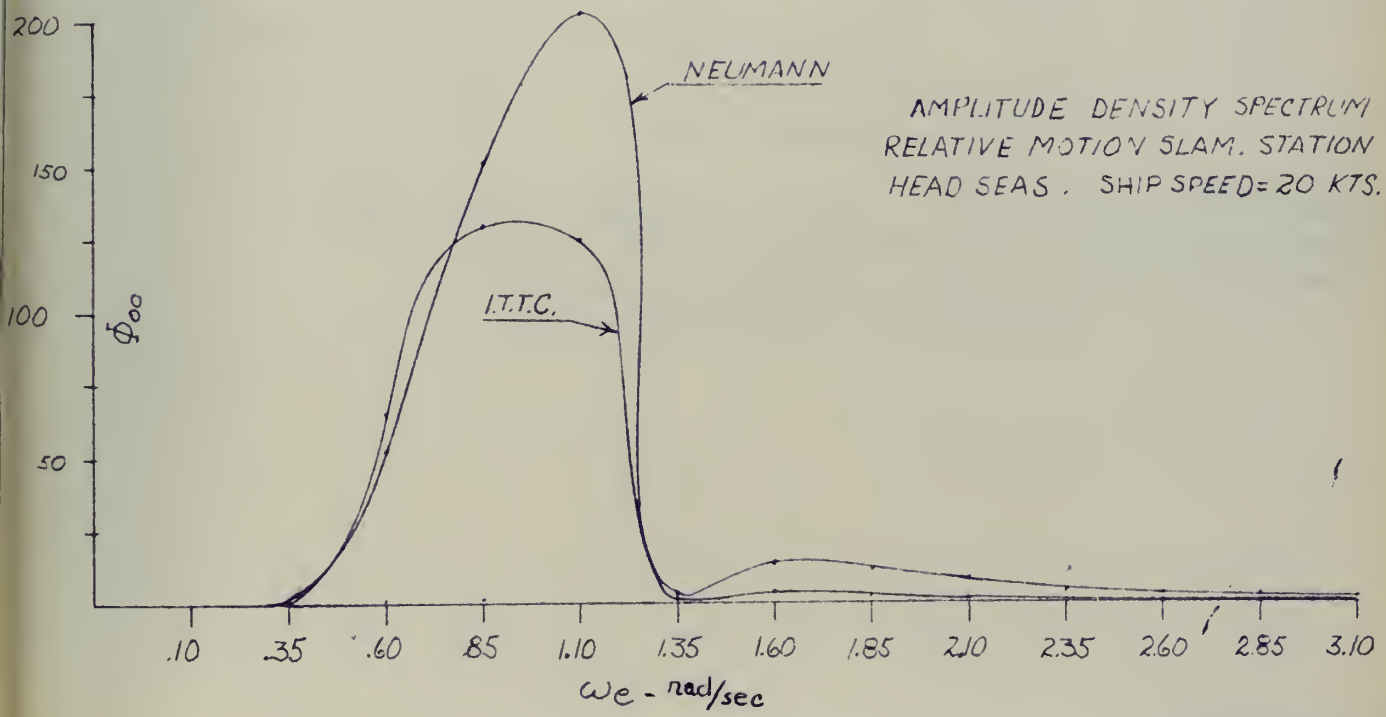


FIGURE IV

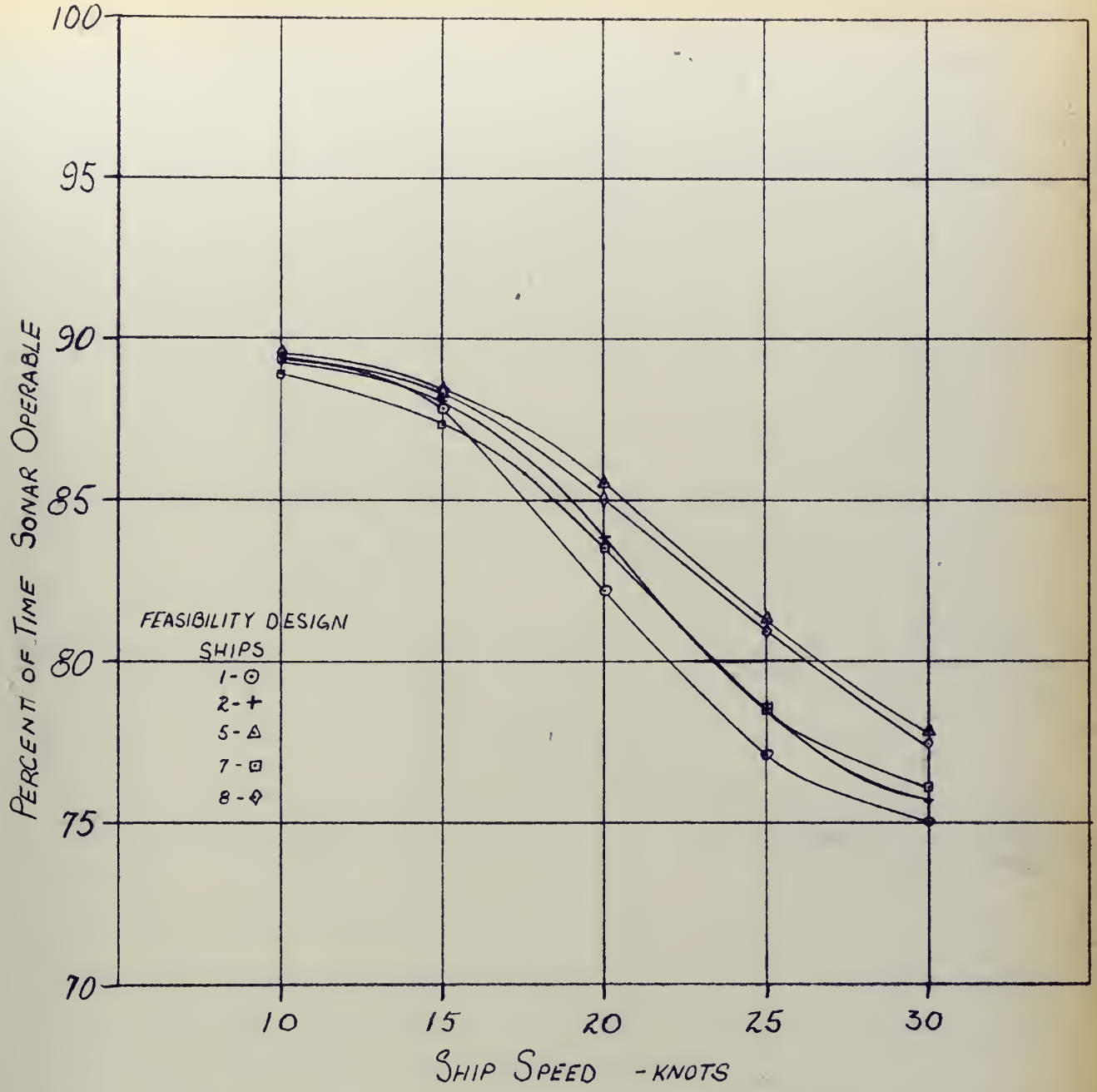


FIGURE V : PERCENT OF TIME THE FEASIBILITY SHIPS COULD BE EXPECTED TO OPERATE WITH THEIR SONAR OPERABLE AT THE LISTED SPEEDS IN HEAD SEAS WITH THE ASSUMED WAVE FREQUENCY DISTRIBUTION

FIGURE V

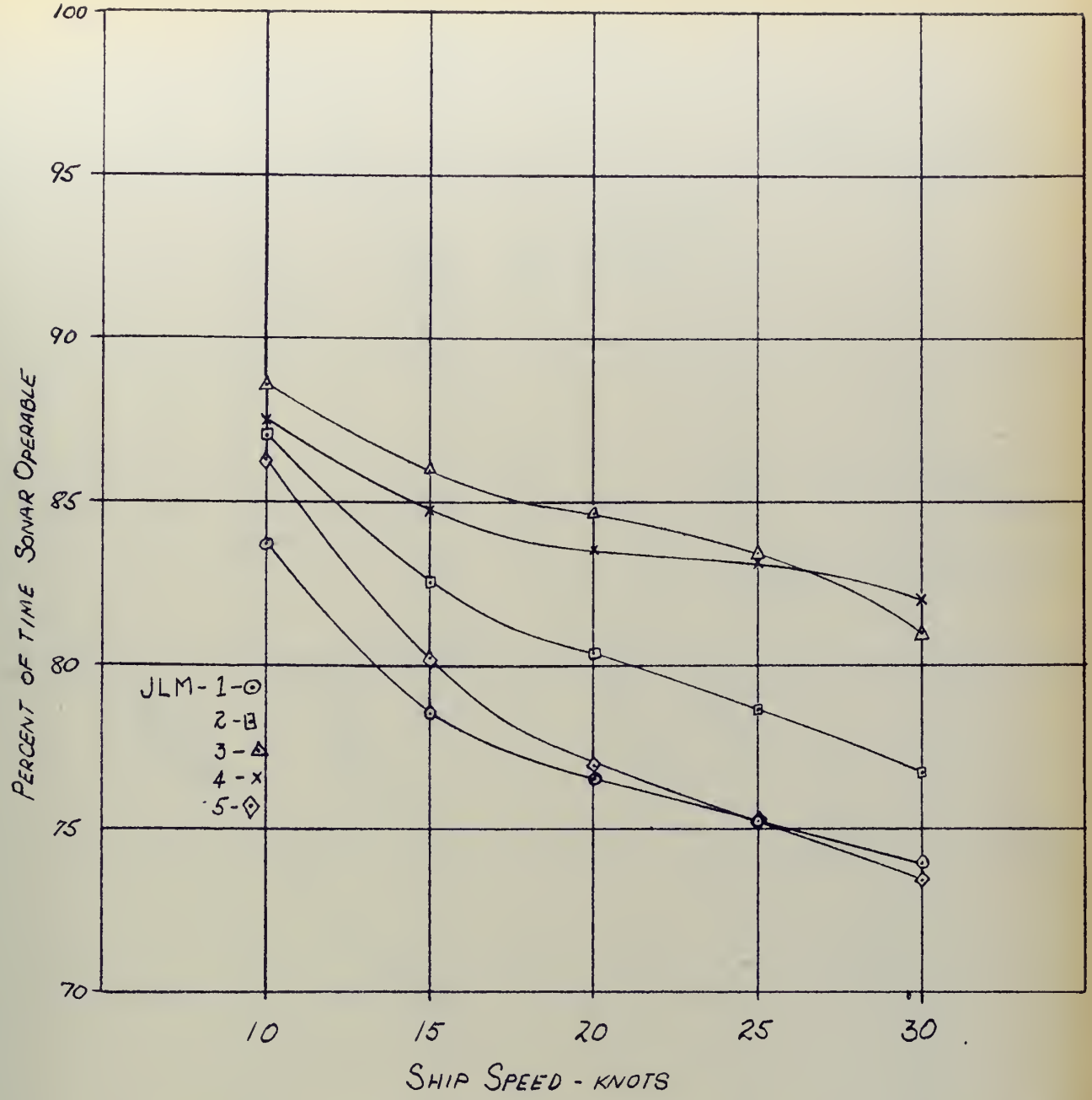
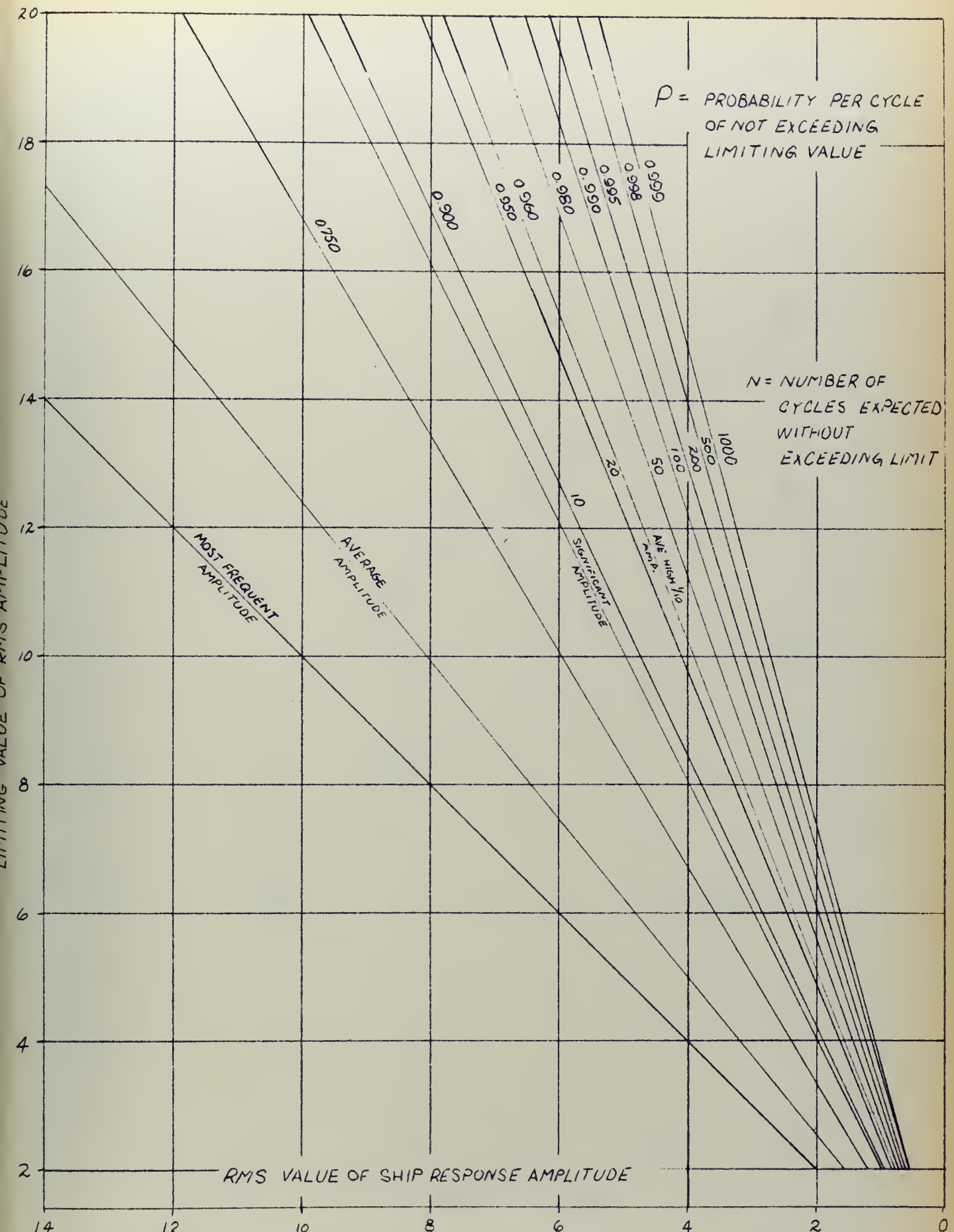


FIGURE VI : PERCENT OF TIME THE JLM SHIPS COULD BE EXPECTED TO OPERATE WITH THEIR SONAR OPERABLE AT THE LISTED SPEEDS IN HEAD SEAS WITH THE ASSUMED WAVE FREQUENCY DISTRIBUTION.

FIGURE VI



LIMITING VALUE OF RESPONSE versus R.M.S RESPONSE FOR VARIOUS PROBABILITIES (RAYLEIGH DISTRIBUTION) FROM [2] by PERMISSION.

FIGURE VII

FIGURE VIII : COMPUTED R.M.S. RELATIVE BOW MOTION VS. SHIP SPEED at SIGNIFICANT WAVE HEIGHT OF 14.5 FT.

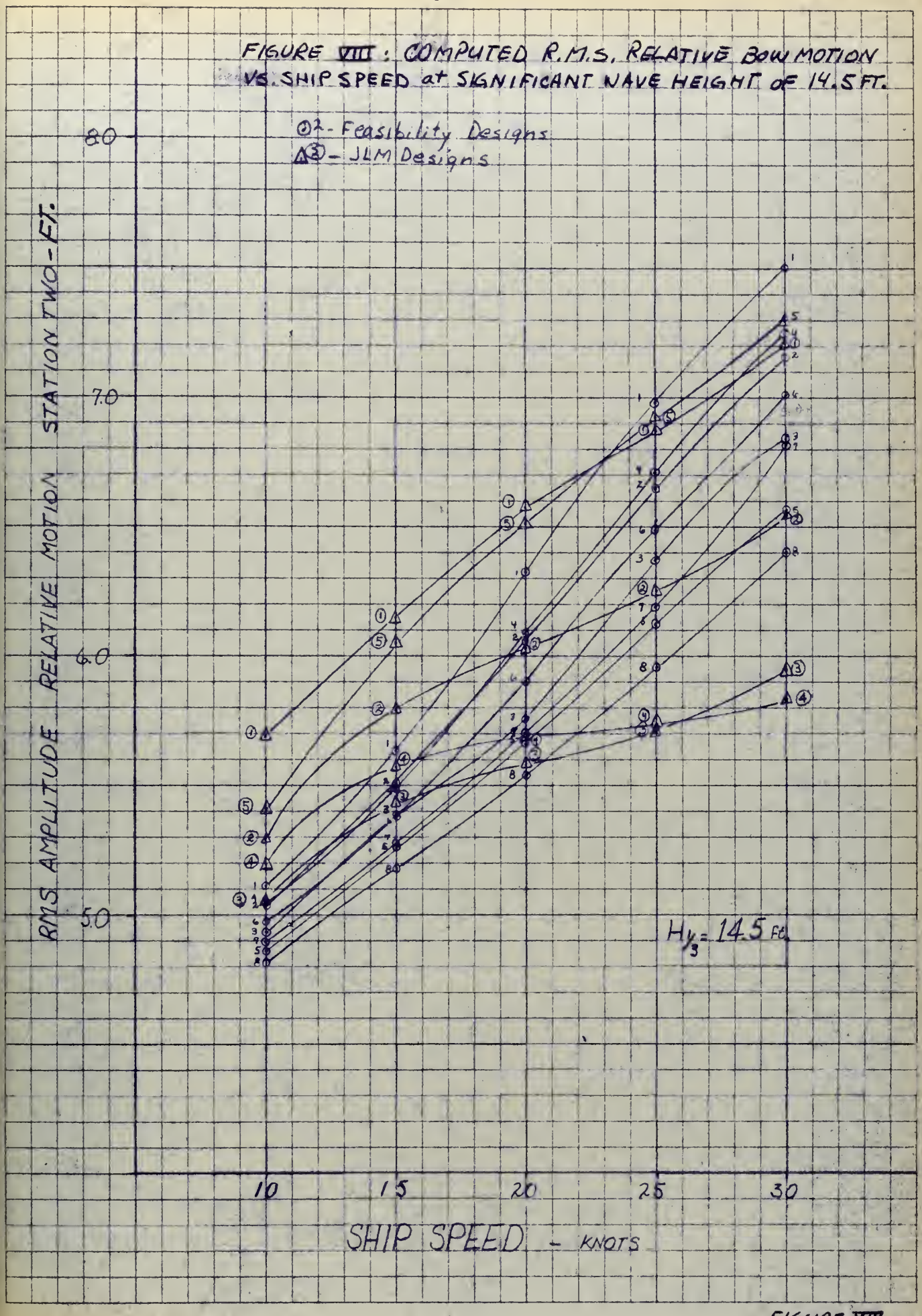


FIGURE VIII

FIGURE IX: COMPUTED R.M.S. RELATIVE BOW MOTION VS. SHIP SPEED at SIGNIFICANT WAVE HEIGHT OF 21.2 FT.

@ - Feasibility Designs
Ⓐ - JLM Designs

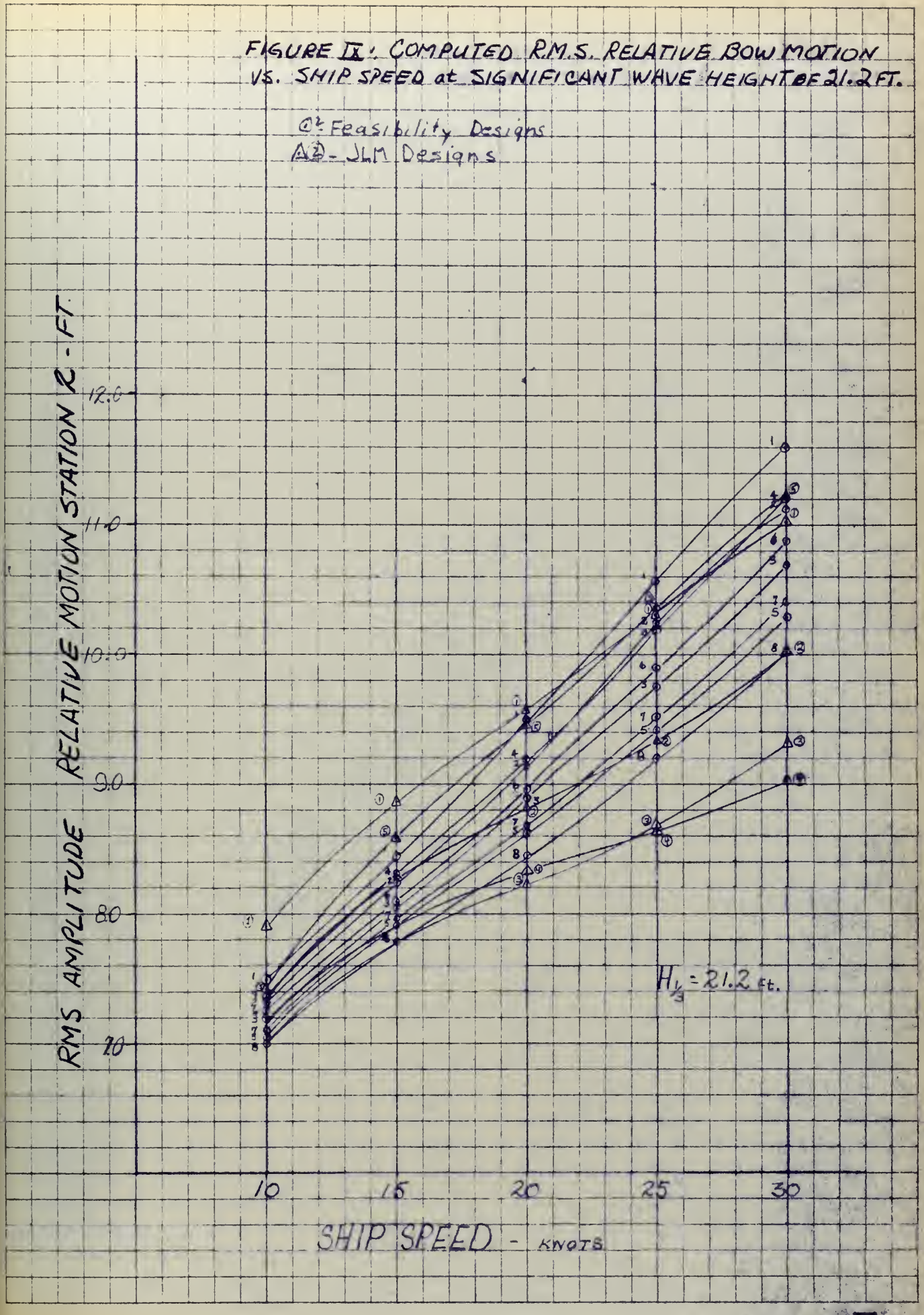


FIGURE IX

FIGURE X : COMPUTED R.M.S. RELATIVE BOW MOTION VS. SHIPSPEED at SIGNIFICANT WAVE HEIGHT of 27.9 FT.

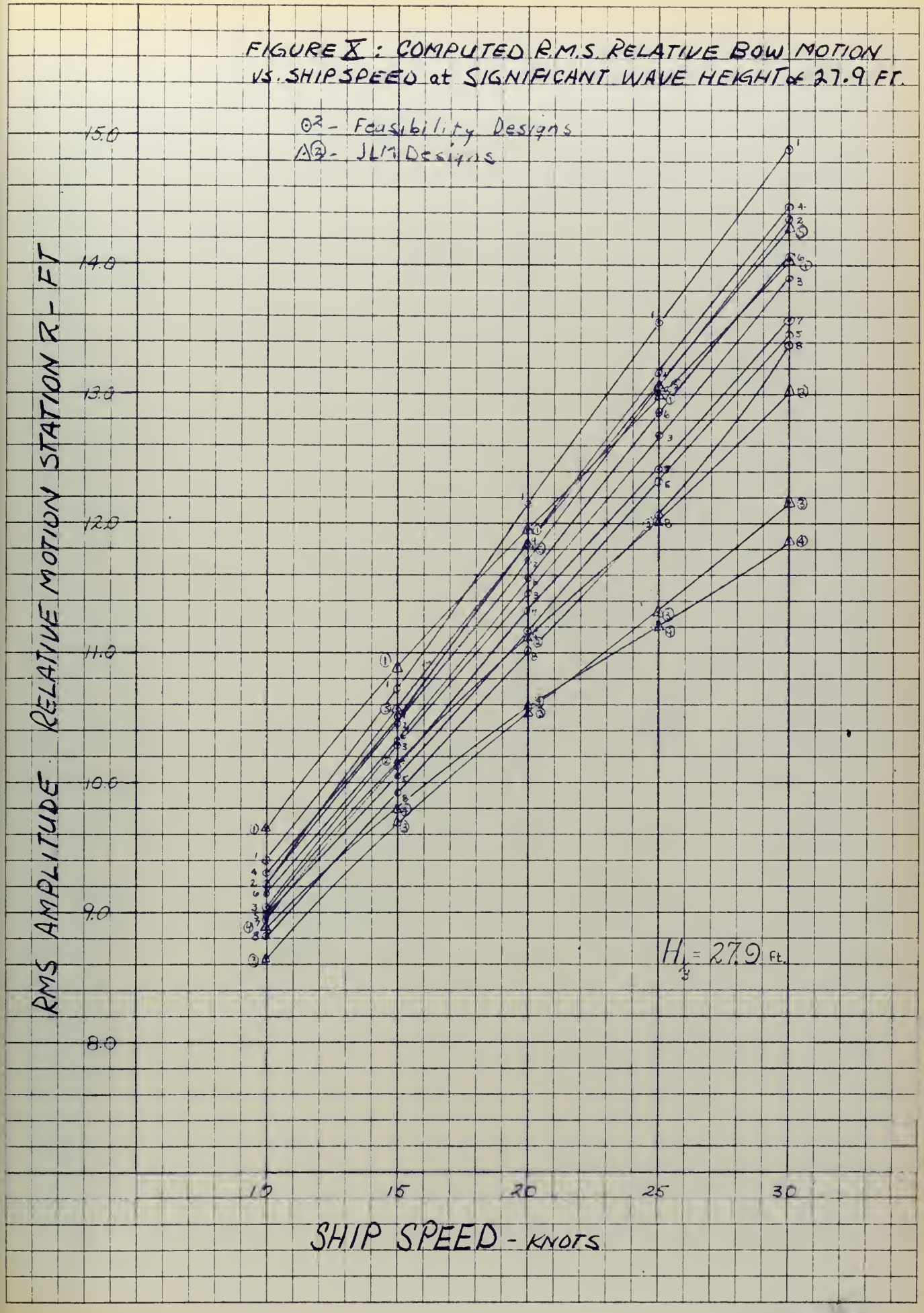


FIGURE X

FIGURE XI: COMPUTED R.M.S. RELATIVE BOW MOTION VS. SHIP SPEED at SIGNIFICANT WAVE HEIGHT OF 34.6 FT.

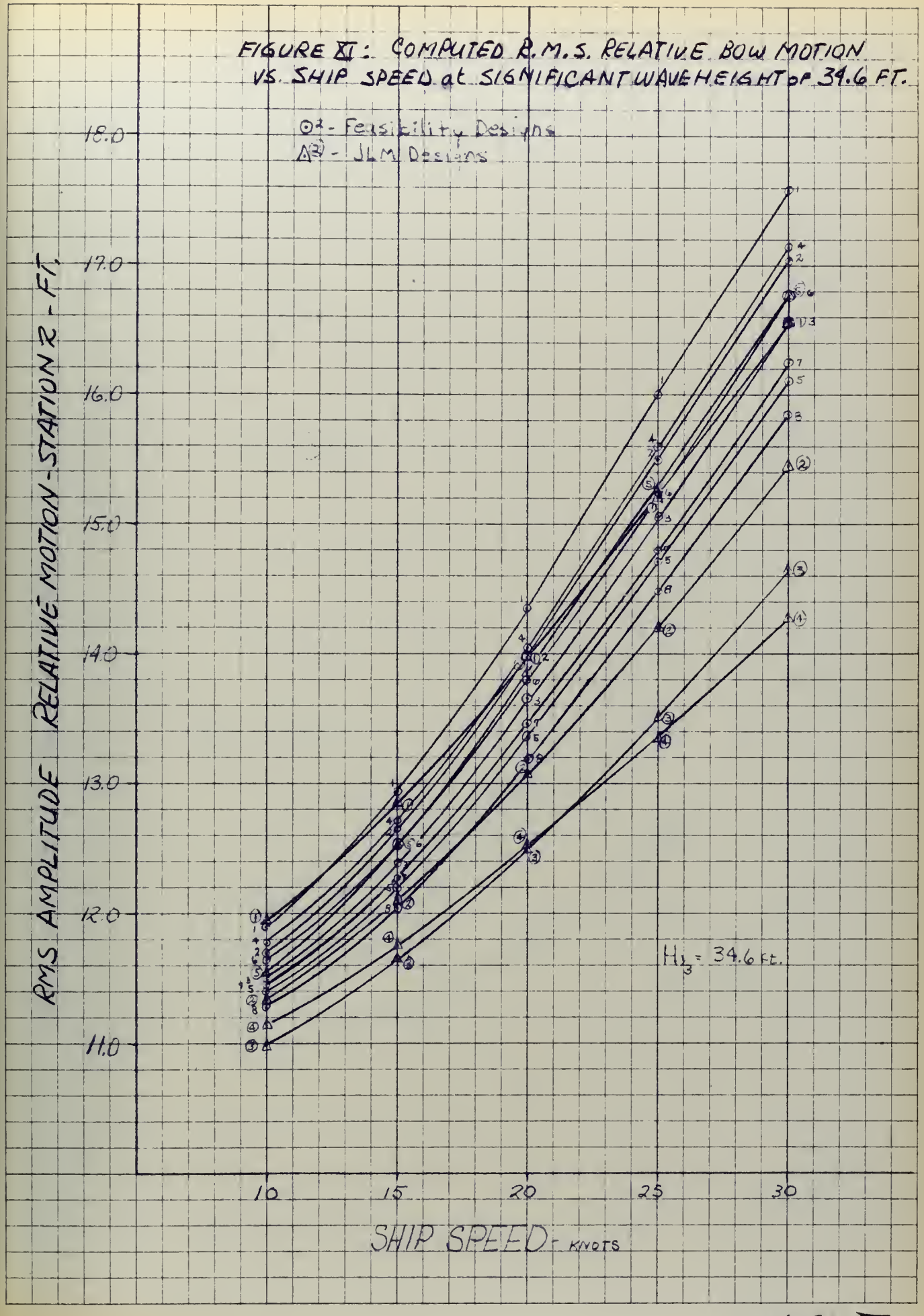


FIGURE XI

FIGURE XII: COMPUTED R.M.S. RELATIVE BOW MOTION VS. SHIP SPEED at SIGNIFICANT WAVE HEIGHT of 41.3 FT.

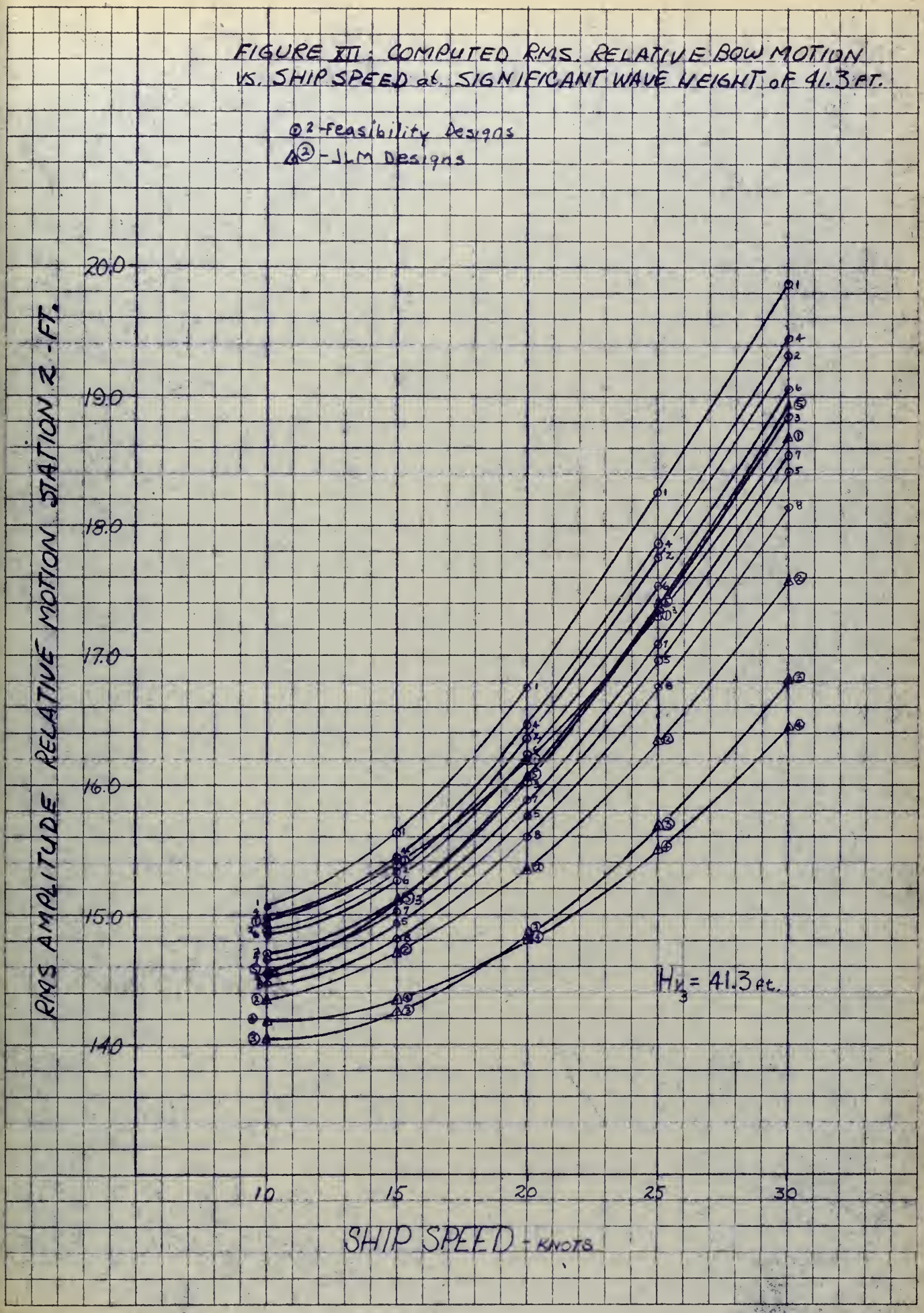


FIGURE XII

FIGURE XIII : COMPUTED R.M.S. RELATIVE BOW MOTION VS. SHIP SPEED at SIGNIFICANT WAVE HEIGHT of 48.0 FT.

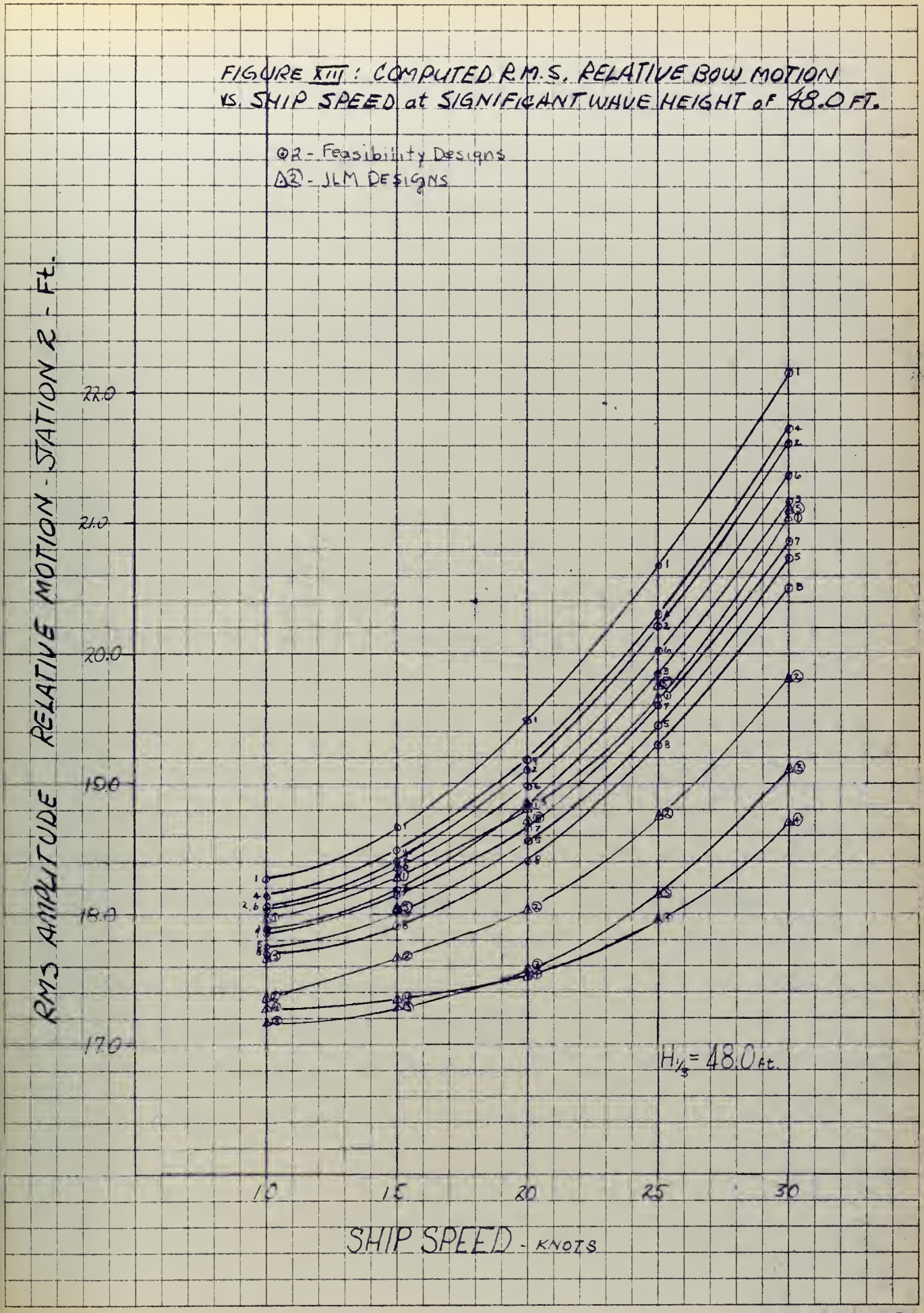


FIGURE XIII

APPENDIX A

Sea Spectrum Calculations: see also 11 and 18

The original program assumed a unidirectional seaway represented by the Neumann energy spectrum

$$\Phi_{(\omega_e)} = \frac{0.001654\, g^2 \pi^3}{\omega^6 \sqrt{1.0 + \frac{4\omega_e V}{g}}} \exp\left[\frac{-2.0 g^2}{W^2 \omega^2}\right]$$

in terms of frequency of encounter, ω_e, where W is wind speed, ω is wave frequency, and V is ship speed.

The I.T.T.C spectrum also assumes a unidirectional seaway and is represented by

$$\Phi_{(\omega_e)} = \frac{0.00810\, g^2}{\omega^5 \sqrt{1.0 + \frac{4\omega_e V}{g}}} \exp\left[\frac{-33.56}{H_{1/3}^2 \omega^4}\right]$$

in terms of frequency of encounter, ω_e, where $H_{1/3}$ is significant wave height as given in Figure III.

The response spectrum is the result of multiplying the sea spectrum by the response amplitude operator. The mean-square value of record of the response is the integrated area under the response spectrum. The root-mean-square of record is the square root of the above area.

The following statistical values can be expressed in terms of the root-mean-square value:

Average Amplitude $.886\sqrt{RMS}$

Significant Amplitude (average one-third highest) $1.416\sqrt{RMS}$

Average of one-tenth highest amplitudes $1.80\sqrt{RMS}$

These three statistical values are computed for each of the five cases:

1. vertical acceleration at slamming station
2. relative vertical motion at the slamming station
3. relative vertical velocity at the slamming station
4. relative vertical motion at the propeller station
5. pitch angle

The slamming station is located .1L aft of F.P. and the propeller station is A.P.

A typical comparison of the two spectra is given in Figure VI. It will be noted that the Neumann Specrum is more severe and hence gives larger values of RMS Relative Motion. The I.T.T.C. Conference in December 1966 chose its spectral formulation based on the work of Pierson and Moskowitz, giving a closer approximation to actual seaway conditions.

The program, as it presently exists, computed the output for this thesis in five minutes per ship case, for an input of five snip speeds and fifteen frequencies of encounter. The eight feasibility ships studied herein required a total of 39 minutes of computer time.

A more detailed discussion of the seakeeping program will be found in [18] and [2].

APPENDIX B

Input and Output Data for Computer Program.

Input Data.

Unless stated, any consistant system of units may be used in the program, the decision being made by the user in the fourth data card. The program is written so that computations can be performed on any number of ships.

Data card 1, Format (4F 10.4)

Bx - Maximum beam

Hx - Maximum draft

Cp - Prismatic coefficient

Cx - Maximum Section coefficient

The following data cards are identical to the MIT Seakeeping program. [18],[2]

Data card 2, Format (A6, I2, 10A6)

Identification card. Information on this card will be printed at the top of each page. ZK11 must appear in columns 5-8, otherwise the user is free to punch any other information on the remaining columns.

Data card 3, Format (5I10)

This card controls the form of output. There are five options. For statistical values to be printed, a "1"

in column 50 instructs the computer to print them. (Output Form 5)

Data card 4, Format (I10, 4F10.4)

Five values should be given on this card:

N - the number of stations. This number will always be 20 if the entire program is run.

L - Length between perpendiculars

γ - specific weight of water - 0.0286 for salt water when displacement is in tons.

g - gravitational acceleration, 32.2 ft/sec^2.

Δ - Displacement of ship in tons.

Data card 5, Format (2F 20.4)

This data card should give two quantities:

1) Radius of gyration (.25L if not known or assumed)

2) Distance from F.P. of center of gravity, (.5L if not known or assumed)

Data card 6, Format (7F 10.4)

This data card should give the seven quantities:

h - wave amplitude (must be unity for statistical calculations)

ω min - Smallest frequency of encounter, 0.

ω max - Largest frequency of encounter

$\delta\omega$ - Increment of frequency of encounter

V min - Smallest ship speed - ft/sec

V max - Largest ship speed - ft/sec

δV - Increment of ship speed - ft/sec

Data card 7, Format (3F 10.4)

The following information should be punched for Neumann Spectrum calculations:

W_{min} - Smallest wind speed, knots

W_{max} - Largest wind speed, knots

δW - Increment of wind speed, knots

The following information should be punched for I.T.T.C. Spectrum:

H_{min} - Minimum significant wave height - ft.

H_{max} - Maximum significant wave height - ft.

δH - Increment of significant wave height - ft.

Note: There are two versions of the above program. One uses the Neumann Spectrum, the second utilizes I.T.T.C. spectrum. Both decks are in binary language (machine language).

The data cards must be followed by a blank card which will end the computer run.

APPENDIX C. Sample analysis calculation using proposed method.

This appendix was added in order to demonstrate the entire process of going from hull dimensions to performance curves by the use of a computer program. Feasibility design number 6 will be used for demonstration purposes. The assumptions are identical to those stated in Solution, Part II.

The KSEA program first reads as input the values of Bx = 48.51; Hx = 17.08; Cp = 0.60; Cx = 0.80, taken from the feasibility output (Table C-1). These values are used in the control program (Table C-2) to compute beam, section area coefficient and draft at each station 0-20 (designated 1-21 for computer application). These values are then stored in memory cells designated DRAFT, SECOE and BSTAR respectively.

They are then called by subroutine SEAKEP and are printed, along with other input data listed in Appendix A. Table C-III shows the actual computer printout of input data. The left column is the waterline curve of beam, the middle column is the section area coefficient, the third column is station draft. These values were computed by the main program. Other data is placed in the computer on punch cards using the formats listed in Appendix A. The computer then calculates statistical responses for each speed selected at each wave height over the complete range of frequency of encounter. The sample output for a ship speed of 15 knots

in a wave height of 34.6 feet is shown in Table C-IV. The circled value of r.m.s. relative vertical motion in Table C-IV was tabulated at 15 knots over the range of significant wave heights, 14.5 - 48.0 feet, and used in line 3 of Table V. This was done at each speed for each of the 13 ships. The r.m.s. value for significant wave heights below 14.5 feet was extrapolated from the r.m.s. vs. wave height curves at constant speed (Figures VIII through XIII). The tabular method was then carried out as described in Table V, resulting in the figure of 88.1% of time that the sonar will be operable at 15 knots for design number 6.

TABLE C-I

SHIP NUMBER 36

CODE =1-27

CP = 0.60 | CP = 0.800

CHARACTERISTICS					
LBP	430.00	455.00	460.00	465.00	470.00
BEAM	32.12	49.62	48.97	48.51	48.09
H	18.14	17.54	17.28	17.08	16.87
DM	36.41	34.04	33.53	33.19	32.84
FB3	21.37	21.50	21.62	21.74	21.85
KG	18.96	17.95	17.72	17.55	17.40
GM	5.21	4.96	4.90	4.85	4.81
CV	2.24	2.02	1.92	1.84	1.76
B/H	2.87	2.83	2.83	2.84	2.85
VLR	1.41	1.41	1.40	1.39	1.38
FR	0.69	0.69	0.69	0.69	0.69
SHP	1.4627.	95701.	92463.	89984.	87700.
PI	1.4627.	95701.	92463.	89984.	87700.
SHPC	10544.	15979.	15822.	15716.	15624.
ELKW	2484.	2385.	2354.	2331.	2311.
COMPLEMENT					
COMP	233.	233.	233.	233.	233.
OFFR	19.	19.	19.	19.	19.
CREW	214.	214.	214.	214.	214.
SPACE					
THV	515407.	460714.	452805.	449126.	445283.
SSV	56222.	55814.	55719.	55656.	55598.
AAH	20926.	20695.	20656.	20638.	20623.
AASS	7028.	6977.	6965.	6957.	6950.
XAAH	0.	0.	0.	0.	140.
NOOK	1.	1.	1.	1.	1.
RDKL	0.	0.	0.	0.	0.
WEIGHTS					
DISP	5917.2	5567.7	5414.2	5357.0	5303.0
W1	1747.1	1571.4	1543.3	1528.9	1514.4
W2	1153.7	1074.4	1047.2	1026.9	1008.3
W3	177.3	176.1	176.4	176.8	177.3
W4	132.9	126.8	125.9	125.4	124.9
W5	509.5	451.4	438.5	430.3	422.9
W6	254.9	238.1	235.7	234.5	233.3
W7	60.0	60.0	60.0	60.0	60.0
MARG	403.5	369.8	362.7	358.3	354.1
WL	4438.9	4068.4	3989.5	3941.3	3895.3
FGM	50.0	50.0	50.0	50.0	50.0
COMP	26.1	26.1	26.1	26.1	26.1
PROV	34.1	34.1	34.1	34.1	34.1
GENS	10.1	10.1	10.1	10.1	10.1
POTW	51.9	51.9	51.9	51.9	51.9
RFW	99.2	92.6	90.2	88.4	86.7
LUBO	19.3	18.3	18.0	17.7	17.5
FUEL	1120.1	1084.2	1073.9	1066.9	1060.9
SWID	0.	0.	0.	0.	0.
AMMO	71.8	71.8	71.8	71.8	71.8
A/C	-0.	-0.	-0.	-0.	-0.
JP5	-0.	-0.	-0.	-0.	-0.
WFL	5921.5	5507.1	5415.7	5358.3	5304.3
NOIT	13	8	8	8	8

TABLE C-II - List of Control Program, KSEA

TEST - EFN SOURCE STATEMENT - IFN(S) -

```
C  PROGRAM FOR INTERPOLATING AREA,BEAM,DRAFT AT STATION FOR ENTRANCE
C  INTO A SEAKEEPING PROGRAM. CURVES SOLVED ARE BASED ON SEAHAWK
C  MODELS JLM SERIES 1 THRU 5.
      DIMENSION Y(81),TR(6),TI(6),ADDA(4),BEEB(4),CGGC(4),UR(6),UI(6),
     1DMASS(21),QUANT(21),SKLAM(21),BSTAR(21),CXFST(21),SXFST(21),
     2CTFST(21),STFST(21),XI(21),DIX(21),ENOXI(21),DRAFT(21),DWEIGH(21),
     3SECOE(21),ABAR(21),SPECM(81),VOMEGA(81),RAOSDD(81),RAORB(81),
     4RAORDB(81),RAORP(81),RAOTHE(81),RSDSDD(81),RSDRB(81),RSDRDB(81),
     5RSDRP(81),RSDTHE(81) , TITLE(12)
     6 ,SP(18), OM(40), ZN(40), DE(40), TN(40), EP(40), OME(4)
     7 ,AN(21),BN(21),HN(21),CAS(21),AS(21),BS(21),HS(21)
      COMMON  Y      , J      , SYMPS  , DXI    , ADDA   , BEEB
      COMMON  CGGC   , ZREAL  , ZIMAG  , TREAL  , TIMAG  , ZNULL
      COMMON  TNULL  , DELTA  , EPSIL  , TR     , TI     , V
      COMMON  DMASS  , QUANT  , OMEGAE , SKLAM  , KRIT   , RO
      COMMON  GRAV   , BSTAR  , CXFST  , SXFST  , ALPHA  , SHNULL
      COMMON  XI     , BETA   , BMNULL , GAMMA  , DIX    , M
      COMMON  WA     , WAVEN  , CW     , ENOXI  , SIGMA  , TAU
      COMMON  FNULL  , EMNULL , DRAFT  , DWEIGH , SECOE  , TMASS
      COMMON  N      , UR     , UI     , ABAR   , PI     , SHREAL
      COMMON  SHIMAG , BMREAL , BMIMAG , YNERT  , VOITH  , RIZA
      COMMON  OMEGA  , MM     , NN     , H      , KK     , W
      COMMON  VOMEGA , SPECM  , RAOSDD , RAORB  , RAORDB , RAORP
      COMMON  RAOTHE , RSDRB  , RSDSDD , RSDRDB , RSDRP  , RSDTHE
      COMMON  RSTSDD , RSTRP  , RSTRDB , RSTRB  , RSTTHE , HELP1
      COMMON  HELP2  , HELP3  , HELP4  , HELP5  , AVESDD , AVERB
      COMMON  AVERDB , AVERP  , AVETHE , SIGSDD , SIGRB  , SIGRDB
      COMMON  SIGRP  , SIGTHE , AVHSDD , AVHRB  , AVHRDB , AVHRP
      COMMON  AVHTHE , CONST  , GSQUAR , DEENFR
      EQUIVALENCE(DRAFT,HS),(BSTAR,BS),(SECOE,CAS)
  500 READ(5,900) BX,HX,CP,CX
  900 FORMAT(4F10.4)
      IF(BX) 600,600,700
  700 AX=CX*BX*HX
      CP2=CP**2
      BN(1) = 0.387108- 1.256049*CP+ 1.027499*CP2
      BN(2) =-5.311799+17.771660*CP-14.416660*CP2
      BN(3) =-0.416799+ 1.013333*CP+ 0.166666*CP2
      BN(4) =-0.394199+ 1.144999*CP+ 0.250000*CP2
      BN(5) =-0.317599+ 1.176666*CP+ 0.333333*CP2
      BN(6) = 4.105199-14.111660*CP+13.916660*CP2
      BN(7) =-0.064199+ 1.436666*CP-0.166666*CP2
      BN(8) =-0.612999+ 3.899999*CP- 2.499999*CP2
      BN(9) =-0.733199+ 4.81999*CP- 3.499999*CP2
      BN(10)=-0.083799+ 3.113333*CP- 2.333333*CP2
      BN(11)= 0.637600+ 1.014999*CP- 0.749999*CP2
      BN(12)=0.922600+ 0.323333*CP-0.333333*CP2
      BN(13)= 0.907200+ 0.304999*CP- 0.249999*CP2
      BN(14)= 0.932199+ 0.255000*CP-0.250000*CP2
      BN(15)= 0.544000+ 1.233333*CP- 0.833333*CP2
      BN(16)= 0.372599+ 1.415000*CP- 0.750000*CP2
      BN(17)= 0.565000+ 0.308333*CP+ 0.416666*CP2
      BN(18)= 2.256599- 5.951666*CP+ 5.916666*CP2
      BN(19)= 0.232599+ 0.540000*CP+ 0.499999*CP2
      BN(20)= 0.080599+ 0.831666*CP+ 0.08333*CP2
```

TEST - EFN SOURCE STATEMENT - IFN(S) -

```
      BN(21)=1.502599- 3.55999*CP+ 2.999999*CP2
      AN(1) =-0.109122+ 0.516402*CP- 0.423280*CP2
      AN(2) = 0.040989- 0.255820*CP+ 0.687831*CP2
      AN(3) = 0.082418- 0.453439*CP+ 1.164021*CP2
      AN(4) = 0.125259- 0.540741*CP+ 1.481481*CP2
      AN(5) = 0.272381- 0.857143*CP+ 1.904761*CP2
      AN(6) = 0.542730- 1.498412*CP+ 2.539628*CP2
      AN(7) = 0.440767- 0.694709*CP+ 1.798941*CP2
      AN(8) =-0.482566+ 3.021957*CP- 1.534391*CP2
      AN(9) =-0.273566+ 2.821957*CP- 1.534391*CP2
      AN(10)= 0.131915+ 2.067989*CP- 1.216931*CP2
      AN(11)= 1.052243- 0.632804*CP+ 0.846561*CP2
      AN(12)= 0.950746+ 0.176984*CP- 0.158730*CP2
      AN(13)=-0.022476+ 3.121428*CP- 2.380952*CP2
      AN(14)=-1.056005+ 6.147089*CP- 4.656084*CP2
      AN(15)=-2.904328+ 11.519570*CP-8.677248*CP2
      AN(16)=-1.106661+ 4.286243*CP- 2.010582*CP2
      AN(17)=-0.073434+ 0.178042*CP+ 1.534391*CP2
      AN(18)= 0.158555- 0.877777*CP+ 2.222222*CP2
      AN(19)= 0.607693- 2.502116*CP+ 3.280423*CP2
      AN(20)=-0.039063- 0.151587*CP+ 0.793651*CP2
      AN(21)=-0.082815+ 0.435185*CP- 0.370370*CP2
      DO 50 I=1,15
   50 HN(I)=1.0
      IF(CP.LT..58)HN(15)=0.043+1.650*CP
      HN(16)=-1.072399+4.731666*CP-2.416666*CP2
      HN(17)=-0.633799+2.696666*CP-0.666666*CP2
      HN(18)=-1.162999+4.062499*CP-1.874999*CP2
      HN(19)=-0.419799+1.217499*CP+0.375000*CP2
      HN(20)=-1.604399+5.356666*CP-3.666666*CP2
      HN(21)=0.463399-1.160833*CP+0.958333*CP2
      DO300 I=1,21
      AS(I)=AN(I)*AX
      BS(I)=BN(I)*BX
      HS(I)=HN(I)*HX
  300 CAS(I)=AS(I)/(BS(I)*HS(I))
      READ (5,903)  CAS(I)
  903 FORMAT  (F10.0)
      PRINT 400,(AS(I),BS(I),HS(I),CAS(I),I=1,21)
  400 FORMAT(4(F10.4,5X))
      CALL SEAKEP
      GO TO 500
  600 STOP
      END
```

TABLE C-III - INPUT TO SEAKEEPING SUBROUTINE SEAKEP

```
ZK11   TEST RUN NO.6   L=465 FEET,CP=0.60,CX=0.80      D.KALB 5/67
   -0          -0          -0          -0          1
   20    465.0000      0.0288     32.2000  5358.3000
0.1639    11.4470    17.0800
7.8198     0.6706    17.0800
12.1857    0.7306    17.0800
18.5696    0.6983    17.0800
24.6625    0.6984    17.0800
31.4442    0.6886    17.0800
35.7907    0.7282    17.0800
40.1178    0.7528    17.0800
43.6006    0.7719    17.0800
45.8032    0.7919    17.0800
47.3749    0.8006    17.0800
48.3451    0.8026    17.0800
48.5197    0.7944    17.0800
48.2771    0.7685    17.0800
47.7388    0.7184    17.0800
46.1621    0.6951    15.3139
43.6590    0.6997    12.7110
39.5647    0.7066    10.2395
35.7324    0.7003     7.6126
29.5716    0.7056     4.9464
21.6648    0.7198     1.9112
         116.2500              232.5000
 1.0000    0.1000     3.3500     0.2500    16.8900    50.6700     8.4450
14.5000   48.0000     6.7000
```

TABLE C-IV

2K11 TEST RUN NO.6 L=465 FEET.CP=0.60.CX=0.80 D.KALB 5/67

SHIP LENGTH = 465.00 FEET.

THE FOLLOWING CALCULATIONS ARE FOR A SHIP SPEED. V=15.000 KNOTS. THE FROUDE NUMBER IS F =0.207

WAVE HEIGHT = 34.60 FEET.

OMEGAE	SPECM	RAOSDD	RAORB	RAORDB	RAORP	RAOTHE
0.	0.	-0.000	-0.000	-0.000	-0.000	-0.000
0.100	0.000	0.000	3.720	0.037	4.208	0.000
0.350	39.720	0.017	2.862	0.351	3.580	0.023
0.600	187.709	0.441	1.757	0.633	0.784	0.132
0.850	118.468	3.796	2.923	2.112	2.567	0.264
1.100	59.861	9.450	3.642	4.407	3.810	0.233
1.350	30.880	0.470	0.722	1.316	0.321	0.010
1.600	16.932	0.605	1.066	2.730	1.828	0.007
1.850	9.878	0.312	0.750	2.567	0.696	0.002
2.100	6.087	0.026	0.999	4.406	1.113	0.000
2.350	3.931	0.021	0.995	5.497	0.955	0.000
2.600	2.641	0.018	0.966	6.530	0.989	0.000
2.850	1.836	0.074	0.949	7.705	0.941	0.000
3.100	1.313	0.026	1.018	9.783	1.050	0.000
-0.000	0.963	0.074	0.964	10.814	0.961	0.000

OMEGAE	SPECM	RSDSDD	RSDRB	RSDRDB	RSDRP	RSDTHE
0.	0.	0.	0.	0.	0.	0.
0.100	0.000	0.000	0.000	0.000	0.000	0.000
0.350	39.720	0.666	113.697	13.938	142.205	0.925
0.600	187.709	82.691	329.882	118.757	147.124	24.729
0.850	118.468	449.681	346.272	250.182	304.100	33.679
1.100	59.861	565.669	218.016	263.800	347.765	13.946
1.350	30.880	14.504	22.290	40.624	9.918	0.295
1.600	16.932	13.637	18.054	46.219	30.954	0.117
1.850	9.878	3.083	7.409	25.357	8.876	0.016
2.100	6.087	0.155	6.082	26.823	6.772	0.001
2.350	3.931	0.083	3.913	21.608	3.754	0.000
2.600	2.641	0.048	2.551	17.248	2.612	0.000
2.850	1.836	0.137	1.741	14.144	1.728	0.000
3.100	1.313	0.035	1.337	12.848	1.379	0.000
-0.000	0.963	0.072	0.928	10.416	0.926	0.000

SLAMMING STATION MEAN SQUARED ACCELERATION = 298.776 FT/SEC/SEC.
SQUARE ROOT OF ABOVE QUANTITY =17.285
SLAMMING STATION AVERAGE ACCELERATION = 14.969 FT/SEC/SEC.
SLAMMING STATION SIGNIFICANT ACCELERATION = 24.458 FT/SEC/SEC.
SLAMMING STATION ONE TENTH AVERAGE ACCELERATION = 31.113 FT/SEC/SEC.

SLAMMING STATION MEAN SQUARED RELATIVE MOTION = 274.606 FEET.
SQUARE ROOT OF ABOVE QUANTITY =16.571 RMS VALUE OF RELATIVE VERTICAL MOTION
SLAMMING STATION AVERAGE RELATIVE MOTION = 14.351 FEET.
SLAMMING STATION SIGNIFICANT RELATIVE MOTION = 23.446 FEET.
SLAMMING STATION ONE TENTH AVERAGE RELATIVE MOTION = 29.828 FEET.

SLAMMING STATION MEAN SQUARED RELATIVE VELOCITY = 223.740 FEET/SEC.
SQUARE ROOT OF ABOVE QUANTITY =14.958
SLAMMING STATION AVERAGE RELATIVE VELOCITY = 12.954 FEET/SEC.
SLAMMING STATION SIGNIFICANT RELATIVE VELOCITY = 21.165 FEET/SEC.

SLAMMING STATION ONE TENTH AVERAGE RELATIVE VELOCITY = 26.924 FEET/SEC.

PROPELLER STATION MEAN SQUARED RELATIVE MOTION = 257.043 FEET.
SQUARE ROOT OF ABOVE QUANTITY =16.033
PROPELLER STATION AVERAGE RELATIVE MOTION = 13.864 FEET.
PROPELLER STATION SIGNIFICANT RELATIVE MOTION = 22.686 FEET.
PROPELLER STATION ONE TENTH AVERAGE RELATIVE MOTION = 28.859 FEET.

PITCH MEAN SQUARED AMPLITUDE =18.751 DEG.
SQUARE ROOT OF ABOVE QUANTITY = 4.330
PITCH AVERAGE AMPLITUDE = 3.750 DEG.
PITCH SIGNIFICANT AMPLITUDE = 6.127 DEG.
PITCH ONE TENTH AVERAGE AMPLITUDE = 7.794 DEG.

TABLE C-V

Calculation of percentage of time that bow sonar would be operable - Feasibility Design 6 at 15 knots in assumed wave distribution.

1	Wave Category (ft)	14.5	14.5	21.2	27.9	34.6	41.3	48.0
2	Wave frequency	0.737	0.156	0.069	0.031	0.0045	0.0020	0.0005
3	r.m.s. value relative motion	(2.30)	5.380	8.108	10.332	12.521	15.269	18.340
4	Product lines 2 x 3	1.695	0.839	0.559	0.320	0.056	0.031	0.009
	Note (b) — σ = .16(3.509) = .561					Total line 4 = 3.509		
5	x= $\frac{6.18\text{-line } 3}{}$	6.918	1.426	-3.438	-7.403	-11.304	-16.206	-21.681
6	Probability of not exceeding r.m.s= 6.18	1.0000	.9230	0.0000	0.0000	0.0000	0.0000	0.0000
7	Lines 2 x 6	0.737	0.144	0.0	0.0	0.0	0.0	0.0
							Total Line 7 = .881	

Notes:

(a) It is assumed that at any particular time the bow sonar is considered operable if r.m.s. $\leq$ 6.18 ft. This value is based on a limiting value of (H - 1) or 16.08 ft where H = 17.08 ft. (From Figure III)

(b) Standard deviation, σ, assumed to be .16 x total of line four or .16 x weighted mean r.m.s.

(c) The quantity X , line 5 is tabulated in statistical handbooks from which line 6 is obtained.

(d) The total of line 7 gives the probability that the sonar will be operable in a unit time. For this illustration 88.1 %. This point is then plotted.

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